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UNDISTURBED SAMPLING AND CYCLIC LOAD TESTING OF SANDS

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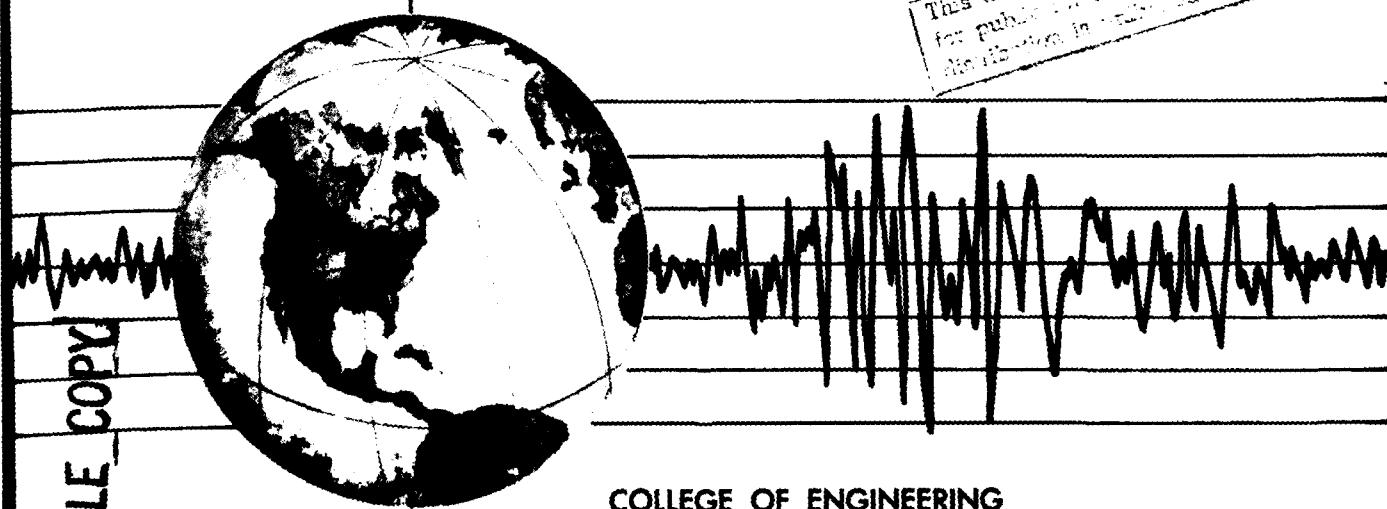
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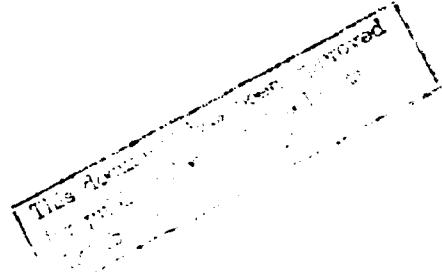
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CHAPTER 1

UNDISTURBED SAMPLING OF SANDS

Introduction

Because of the increasing need to construct or evaluate critical
structures such as earth dams and nuclear power plants, increasing
emphasis in such investigations has been placed in testing high quality
undisturbed samples. It has long been recognized in soil mechanics
that evaluation of the appropriate engineering properties of clay soils
such as strength, compressibility or permeability requires the performance
of laboratory tests on virtually undisturbed samples. However, it is only
recently that similar recognition has been given to testing undisturbed
samples of sand. Sampling of sands, particularly saturated loose sands,
presents special problems, and has been considered to be extremely dif-
ficult when compared with clay sampling. This is mainly due to the fact
that deposits of sands often have unstable structures so that the advance
of even a very thin-walled sampling tube may disturb the structure, result-
ing in a significant change in the void ratio or other significant char-
acteristics. In spite of this, the importance of avoiding sample distur-
bance and the resulting consequences in obtaining samples of sands was
recognized early in the practice of soils engineering. Starting with the
pioneering work of Hvorslev (1949), improved methods have been developed
by Bishop (1948), Osterberg (1952), Nixon (1954), and Serota and Jennings
(1957) to sample cohesionless soils below the ground water table so that a
change of the properties during sampling is prevented or minimized. How-
ever, mainly because of the difficulties in preventing volume changes and

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the loss of sand from the sampling tube during withdrawal, it has been nearly impossible to obtain truly undisturbed samples of sand. Consequently, over the years indirect methods such as the standard penetration test (SPT) or the cone penetration test (CPT) have been widely used to determine the in-situ characteristics of cohesionless deposits; and until recently, there had been little interest in developing new or improved sampling methods compared with the situation about 20 years ago.

In the past ten years, however, rapid development of the finite element method of analysis requiring reliable stress-strain relationships for soils, and the analyses used in earthquake engineering such as evaluating the dynamic response of the ground or liquefaction of saturated sandy soils have shown remarkable progress (Seed, 1968, Seed, 1976, and Yoshimi et al., 1977) and the need for improved data on dynamic soil properties. Accordingly, the dynamic behavior of soils has been the subject of intensive research. Much of this research, involving measurement of dynamic strength parameters, has been performed on reconstituted specimens. However, it is now generally recognized that the behavior of reconstituted and undisturbed samples under cyclic loading conditions can be considerably different (Seed, Arango and C'an, 1975, Mulilis et al., 1975, and Marcuson et al., 1978), and that the dynamic characteristics of in-situ soil deposits are usually much more closely represented by high quality undisturbed samples than by even the best reconstituted specimens. Accordingly, the practice of undisturbed sampling is becoming more widespread.

Significance of Undisturbed Sampling to Cyclic Load Testing of Sands and Objectives of Present Study

On the basis of the results of extensive cyclic load tests reported in the literature on reconstituted and undisturbed specimens of sands, it

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has been recognized that the liquefaction characteristics of in-situ deposits are significantly influenced not only by the density of the deposit but by such factors as the structural arrangements of the sand grains (Ladd, 1974, Mulilis et al., 1975, Mitchell et al., 1976, and Marcuson and Townsend, 1976), the seismic history of the deposit (Finn et al., 1970, and Seed et al., 1975), the in-situ lateral stress conditions (Seed and Peacock, 1971) and the age of the deposit (Seed, 1976, Donovan and Singh, 1976, and Mulilis et al., 1977). In order therefore to make a reasonable estimate of the true resistance to liquefaction of an in-situ deposit, the effects of these factors should be accounted for in a laboratory testing program. One approach is to simulate or reconstruct the true field characteristics in laboratory specimens. However, this would require an evaluation of all the factors listed above. Except for the possible use of the formation factor (Arulanandan, 1975, and Seed et al., 1975) and in-situ measurements for estimating the in-situ structure of sands, undisturbed sampling appears to be the only promising alternative. Therefore the classical problem of undisturbed sampling of sands has acquired a renewed importance in recent years among researchers and practicing engineers; and efforts in the geotechnical earthquake engineering field are being directed towards obtaining better quality undisturbed samples which will hopefully maintain the effects of the factors listed above. How this is to be achieved is not yet clear. There is clearly a need to understand, evaluate and minimize the influence of sample disturbance on cyclic strength characteristics.

Undisturbed samples obtained by using improved or highly sophisticated thin-wall samples or by employing block sampling techniques have generally been found to be stronger (Silver et al., 1978, and Horn, 1978)

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than samples obtained in undisturbed sampling tubes, and the measured differences in the cyclic strength of undisturbed and reconstituted specimens tested at the same density have been attributed to the effects of the various factors mentioned above. However little has been done to clarify the degree of disturbance which takes place during sampling. Even perfect sampling with no mechanical disturbance will result in a change of the soil stress-strain properties due to the change in effective stresses. Unless sampling is carried out from deposits of known dynamic characteristics, qualitative assessment of the effects of disturbance remains unresolved. Yet there are often no reliable techniques for measuring the in-situ characteristics to permit an evaluation of the effects of sample disturbance.

Whereas in the case of clays, various laboratory methods have been developed to reduce the effect of sample disturbance on measured static strength properties, and empirical methods have been formulated to account for disturbance on measured strength, in soil dynamics no such procedures have been developed for sands.

The authors know of only one study where laboratory investigation of the influences of sampling disturbance was made by sampling from deposits of known dynamic characteristics (Mori, Seed, and Chan, 1978). These investigators studied the effects of driving or pushing a sampling tube into sand beds with prior strain and known characteristics. In spite of the great care taken in sampling, handling and testing, the test results indicated that for the case of the sand tested (Monterey #0) virtually all of the effects of the prior strain history were lost. Since Mori et al. sampled from beds of sands which had their confining pressures removed prior to sampling, it is difficult to evaluate the degree of disturbance due to tube insertion alone. Accordingly this particular source of

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disturbance and its accompanying effects has yet to be resolved by developing techniques to extract samples while the confining pressure is maintained, thereby simulating currently used methods of in-situ sampling of sands.

Volume changes have been reported in carefully conducted laboratory experiments involving fixed piston sampling, while a known vertical overburden was maintained, by Marcuson and his co-workers at the Waterways Experiment Station (Marcuson et al., 1977), and in carefully performed block sampling by Horn (1978). However, often transporting and handling of sand samples can cause as much or even more disturbance than actual sampling. Clearly there is a need to evaluate the degree of disturbance and its accompanying effects on the cyclic strength characteristics of sands in the hope of providing guidance for engineers to take into account, eliminate or minimize the effects of these sources of disturbance. Special procedures such as freezing of samples prior to sampling and handling should also be investigated in the hope that this would maintain the in-situ structure. Accordingly the studies described herein were carried out:

1. To investigate the influence of tube sampling, under simulated field conditions (by maintaining the confining pressure), on the cyclic load characteristics of sands.

2. To evaluate the effects of block sampling on the cyclic load characteristics of sands.

3. To study the effects of currently used methods of shipping and handling samples in terms of the disturbance it may produce and the accompanying effects on cyclic load characteristics of sands.

4. To investigate if a freezing technique can be used to obtain truly undisturbed samples of sands.

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Discussion

It was in 1949 that Hvorslev's monumental work on subsurface investigation was published. Since then the general state of subsurface exploration practice in deposits of sands has not advanced significantly. Much effort and money have been spent on the development of indirect techniques such as the Standard penetration test and the Dutch cone penetration test. These techniques are based on empirical correlations of penetration resistance, overburden pressure and soil type with other soil characteristics and their use has been widespread because they provide simple, quick and economical means to evaluate in-situ properties. However often the correlations developed and the manner in which these tests are carried out have been questioned by reputable engineers. The reliability of an empirical relation is largely dependent upon the amount of data that has been collected. Nevertheless, properly conducted in-situ tests can be of tremendous value, especially when they avoid problems associated with sample disturbance. However the ability to control soil loading or soil response is sacrificed. With the increasing need to exploit more difficult sites and to build larger and more critical public projects such as dams and nuclear power plants, increasing emphasis is being placed on testing high quality undisturbed samples. Good undisturbed samples provide the opportunity to study the behavior of the soil under any stipulated design conditions. In a controlled laboratory atmosphere, important insights can be gained into the parametric effects of different variables affecting the response of a soil deposit to earthquake loading conditions--effects which are difficult to study in-situ. Accordingly it seems to be important to study the influence of sample disturbance on soil test data, leading

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thereby to improved sampling techniques or means to account for distur-

bance in evaluating the in-situ characteristics of sand deposits.

CHAPTER 2

THE SAMPLING DISTURBANCE IN SANDS:
ITS EVALUATION AND INFLUENCE ON STRENGTH PROPERTIES

A thorough understanding of the nature and influence of sample dis-
turbance is essential before attempting to account for or develop methods
of minimizing or preventing sample disturbance. Accordingly in this
chapter the nature of disturbance in sands and the results of previous
investigations of its magnitude and effects are evaluated and examined.
Finally, previous studies of the influence of sample disturbance on the
cyclic strength characteristics of sands are critically reviewed.

2.1 The "Truly Undisturbed", "Undisturbed", and "Disturbed" Sample

It should be understood at the outset of any study of sample dis-
turbance effects that, except possibly through the use of freezing, there
is no such thing as a "truly undisturbed sample" extracted from a bore-
hole. Even a perfect sampling device with no mechanical disturbance will
result, on removal of the soil sample from the surrounding soil mass, in
changes in stresses which had been originally acting on the boundaries of
the sample; thus stress release may, in turn, cause changes in grain
structure which will change the stress-strain characteristics of the soil
specimen. Ladd and Lambe (1963) defined a "perfect sample" as a sample
which has not been disturbed by the boring, sampling and trimming opera-
tions but which has been subjected only to stress release when it is
removed from the ground.

The term "undisturbed soil sample" as it is generally used in
geotechnical engineering is intended to mean a sample which has been

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disturbed so little that it can be used for the laboratory determination
of the strength and compressibility characteristics of the soil in-situ
without any significant errors. In other words, an undisturbed sample
is generally one which is obtained with samplers and sampling techniques
designed to preserve as closely as possible the natural structure and
engineering characteristics of the material. In his classic treatise on
soil sampling, Hvorslev (1949) suggested the following requirements for
an undisturbed sample:

    1.   No disturbance of the soil structure.

    2.   No change in water content or void ratio.

    3.   No change in constituents or chemical composition.

A "disturbed sample" may be defined as one which contains all of
the constituents of the in-situ material in proper proportions but which
has suffered sufficient disturbance to its structure so that the results
of laboratory tests to determine its engineering properties would not be
properly representative of the materials in-situ.

2.2 The Sampling Disturbance in Sands and Its Evaluation

Whereas several definitions of sampling disturbance in clays have
been used to assess the quality of an undisturbed sample, there appears
to be none exclusively developed for sands. For instance, in clays Ladd
and Lambe (1963) proposed the ratio of residual effective stress for a
perfect sample to the residual effective stress for the taken sample.
Noorany and Seed (1965) defined the difference between the residual
effective stress of a perfect sample and that of the taken sample as a
measure of disturbance. Again in the case of clays, Berre and Bjerrum
(1973) used the volume change when the sample was consolidated in the

laboratory under the same stress conditions as those in-situ as a measure of sample disturbance.

In contrast, little has been done to establish means to evaluate the quality of sampling in sands so that meaningful assessments of sampling accuracy could be made. Hvorslev's (1949) studies (1938-48) still remain the principal basis for evaluating the degree of disturbance of this type of soil. According to Hvorslev, the degree of disturbance is proportional to the area ratio and the clearance ratio of the sampling tube used in obtaining the sample where

$$\text{Area Ratio} = \frac{D_o^2 - D_i^2}{D_i^2} \times 100$$

where D_o = outside diameter of sampling tube.

D_i = inside diameter of cutting edge at entrance to the tube.

and $\qquad \text{Clearance Ratio} = \frac{D_s - D_i}{D_i} \times 100$

where D_s = inside diameter of the sampling tube.

D_i = inside diameter of cutting edge at entrance to the tube.

Furthermore, other things being equal Hvorslev considered that samples were less disturbed if the sampling tube was pushed into the sand rather than being driven. These concepts do not lend themselves readily to quantitative evaluations of sample disturbance.

In recent years as the practice of undisturbed sampling of cohesion-less soil has become more common, increased attention appears to have been given to factors such as the area ratio and the clearance ratio of the sampling tube. However, as pointed out in Chapter 1, the effects of

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sample disturbance in sands are more significant for dynamic characteristics due to the small strain levels at which they are often measured, and a more rigorous basis is required to evaluate the quality of samples extracted to study the dynamic and cyclic strength characteristics of in-situ materials.

Until about six years ago it was generally believed that the primary effect of sample disturbance on sands was to change the density or relative density of the sample. As a result, a number of studies were undertaken to investigate this effect. More recent investigations have shown that sampling disturbance may affect not only density but also soil structure, stress history, and cementation. While it is important to evaluate the effects of disturbance on each of these factors, the effects on dry density have received greatest attention and are reviewed in the following section.

2.3 Effect of Sampling on Dry Density

The U. S. Army Engineers were the first (1950 and 1952) to carry out systematic studies of the influence of sampling disturbance on changes in dry density of sands. A large tank was used to prepare artificial deposits of sand. Undisturbed sampling below the water table was carried out by using Hvorslev's fixed piston sampler and the resulting changes in dry density values were investigated. It was found out that the void ratio of a loose cohesionless soil tends to become smaller by disturbance during sampling; on the other hand, the void ratio of a dense cohesionless soil ($D_r > 75\%$) tends to increase by disturbance due to sampling.

The Corps of Engineers at the Waterways Experiment Station have recently (1972-77) extended the previous work to evaluate methods of

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determining in-situ densities. Since 1972, a comprehensive laboratory investigation program to evaluate the characteristics of undisturbed sand samples in terms of changes in dry density has been carried out by WES engineers (Marcuson and Bieganousky, 1976; Cooper, 1976; Marcuson, Cooper and Bieganousky, 1977; and Bieganousky and Marcuson, 1976a,b). Hvorslev's fixed piston sampler and drilling mud were used to accomplish sampling from a 4 ft. diameter and 6 ft. high specimen of sand deposited in a "stacked ring" container. On the basis of comparisons between the sampled density versus placed density, Marcuson et al. (1977) suggested that the sampling accuracy was within ±3.4 pcf for 95 percent of the sampling conducted at relative densities ranging from 20 percent to 60 percent. It was further concluded that the sampling tends to slightly densify loose sands (D_r = 40%) and to slightly loosen denser sands ($D_r \simeq$ 50%). Marcuson et al., however, pointed out that a more meaningful assessment of sampling accuracy would have been made if it had been possible to exercise better control of the placement density during the study. Fig. 2-1 shows the comparison of their test results.

Geotechnical Engineers Inc. (1976) obtained comparative data on densities of block samples and densities from in-situ tests made using a 12 inch diameter core on dense sands from a nuclear power plant site in Massachusetts. This data was reported by Horn (1978) and is shown in Fig. 2.2. The undisturbed samples carved in test pits had dry unit weights that were typically lower than the corresponding values obtained by means of in-situ density tests, the average difference being on the order of 2 lbs./ft.^{3}

Kobayashi and Matsumoto (1977) made a comparison of densities for loose sand filled in a tank having a diameter of 2.5 m and a depth of 3 m.
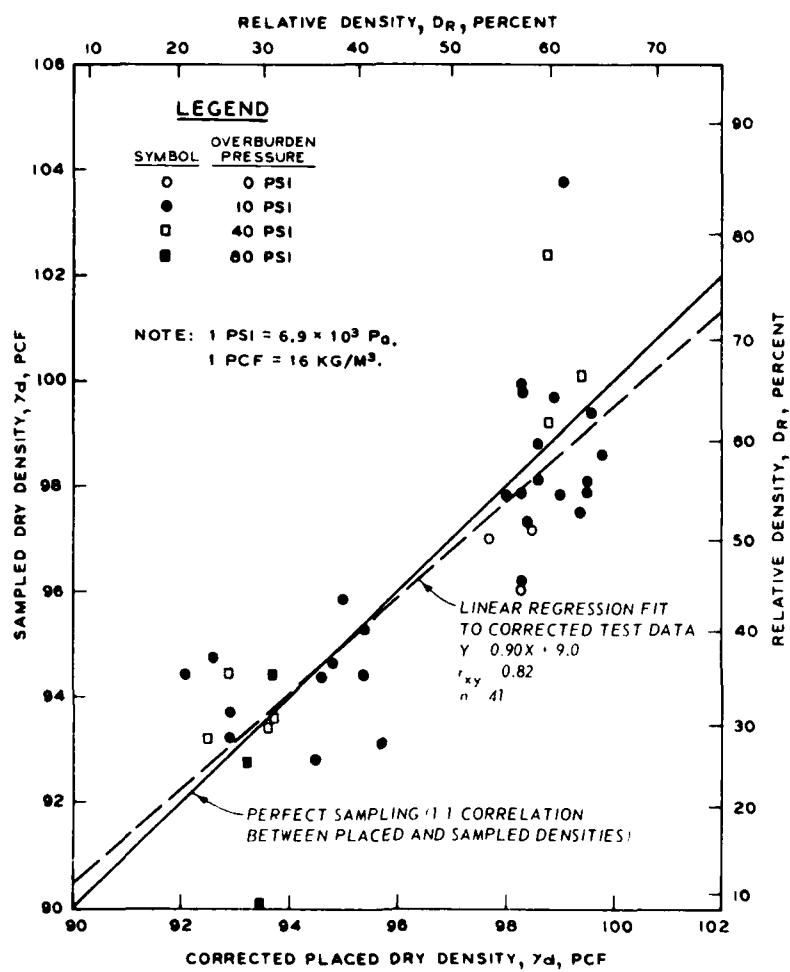
FIG. 2-1   EFFECTS OF SAMPLING ON DENSITY OF SAND

(After Marcuson et al., 1977)
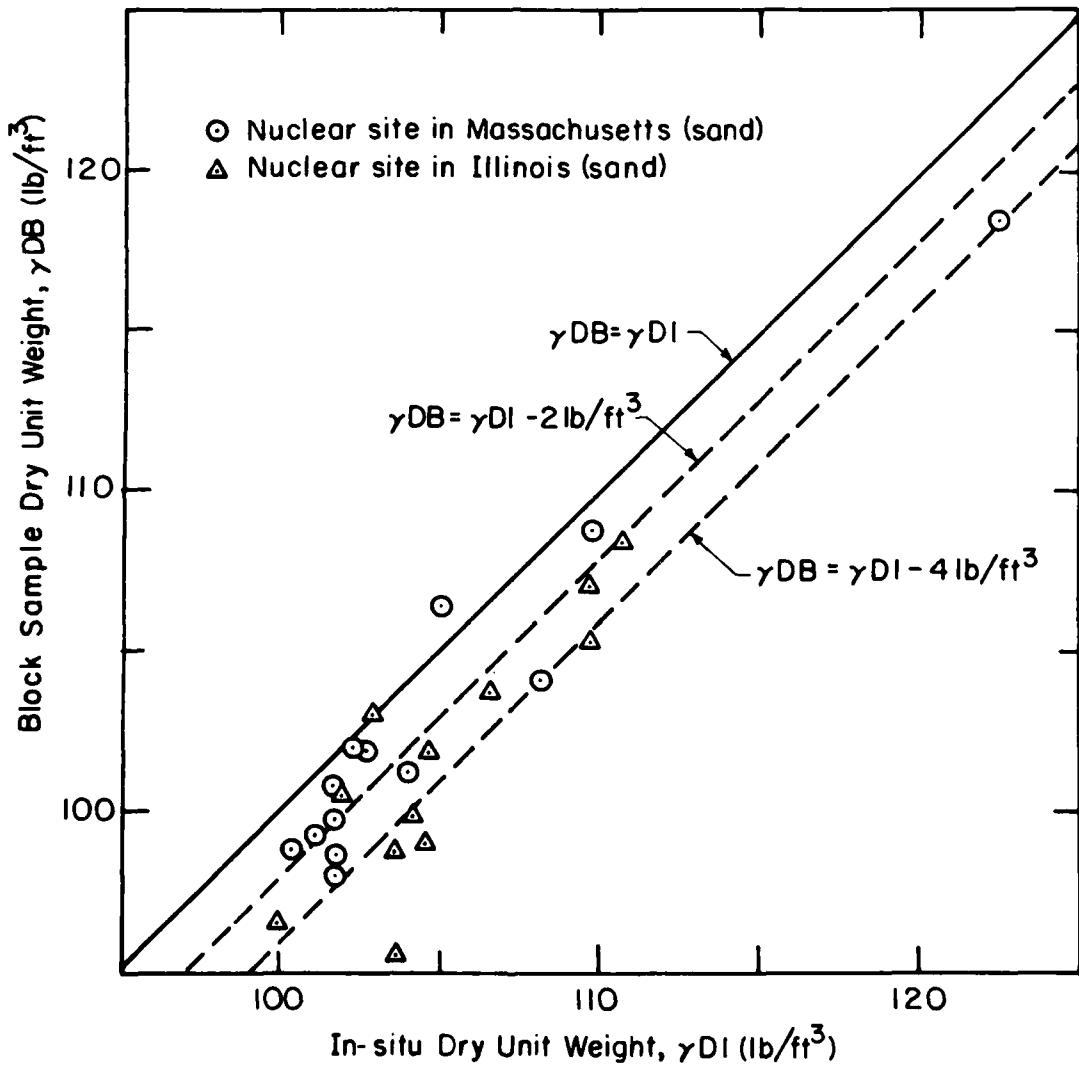
FIG. 2-2   DRY UNIT WEIGHT DETERMINATIONS BY BLOCK SAMPLING AND
IN-SITU METHODS

(After Horn, 1978)

Dry sand was filled in the tank by compaction, then saturated. A sur-charge of 2 tons was applied on top of sand in a manner similar to that used by Marcuson et al. (1977) to create confining pressure. Samples were taken by a thin wall sampler. The average sample density ($e = 0.69$) was a little higher than the average density ($e = 0.74$) in the tank.

Seko and Tobe (1977) prepared a sand "specimen" in a container 1/2 m in diameter and 1 m in height by compacting moist sand in layers (each layer being 10 cm thick). No surcharge was used. The samples were taken from the specimens by using four types of samplers: two of the drive type and two "rotary type" sand samplers. The "rotary type" sampler was similar to the Denison type sampler. The sampling was performed on unsaturated specimens. The void ratio "e_2" of the taken sample was compared with void ratio "e_1" of the specimen in the container. It was found that many values of "e_2" of the taken samples were smaller than the corresponding "e_1" values of the specimen in the container when "e_1" was larger than about 0.65. The opposite was true when "e_1" was smaller than about 0.65. Based on these results, Seko and Tobe suggested that this sand has positive dilatancy (i.e., loosens by sampling) when the void ratio is less than 0.65 and a negative dilatancy (i.e., densifies by sampling) when the void ratio is larger than about 0.65.

Horn (1978) reported results of dry unit weights determined from block-samples and from in-situ tests made in dense sands. Density deter-minations were made in test pits excavated in these sands which had been dewatered with perimeter well points. In-situ density tests were made at various elevations by using the Washington Densometer. Block sampling was carried out at the same elevations by carefully carving block specimens. Figure 2-2 shows a plot of dry unit weights determined from block samples

against dry unit weights determined from in-situ tests. In spite of considerable scatter, the dry unit weights of block samples were generally 3 pcf to 4 pcf lower than those determined from in-situ tests. Horn further reported that a similar trend has also been noted in the case of a variably cemented deposit of sand at another site. One possible explanation advanced for the in-situ density being higher than that of the block samples is that the hole that is dug in dense sand for in-situ density determination has a tendency to squeeze, causing the in-situ density results to be too high. On the other hand, the high degree of arching available in dense sands should minimize such squeezing (Horn, 1978).

Salomone et al. (1978) compared density data obtained using Pitcher, Denison and block sampling techniques with the data obtained from in-situ density tests. Dry densities (75 to 114 pcf) of the Pitcher and Denison samples were higher than those of the block samples (73 to 93 pcf) indicating a densification by Pitcher and Dension samplers. The dry densities (77 to 96 pcf) obtained by the in-place density procedures were approximately the same as from the block samples. It should be noted, however, that this investigation was carried out on variably cemented Vincentown sand, and therefore for typical uncemented sands, disturbance effects are likely to be more pronounced in terms of change of density due to sampling.

2.4 Influence of Sample Disturbance on Dynamic Properties

Seed et al. (1975) showed that dynamic properties depend on:

1. Density

2. Fabric or structure

3. Seismic history

4. Period of sustained load

5. In-situ lateral stress conditions.

Therefore, the effects of sample disturbance on all of these need to be considered.

On the basis of test data on measured cyclic strengths of high quality undisturbed samples and variably disturbed or reconstituted samples, Seed et al. (1975) pointed out that allowance for sample disturbance should be made and suggested that correction factors for change in density, change in structure, change in sustained load effect and change in seismic history effects are needed. A comparison of test data on undisturbed and remoulded samples compiled by Mulilis, Chan and Seed (1975) was presented by Seed et al. to demonstrate the significance of testing undisturbed samples. Test data indicated that the stress ratio causing 100 percent pore pressure ratio in undisturbed samples was characteristically between 0 to 45 percent higher than those of samples prepared by tamping moist sand in the laboratory.

Seed (1976) and later Mori, Chan and Seed (1978) showed that the influence of sample disturbance may be minimized by attempting to reconstruct the true field characteristics on a high quality undisturbed sample by following special procedures. or instance, the effect of reconsolidation on cyclic strengt. characteristics of undisturbed samples obtained from a heavily overconsolidated deposit was demonstrated by Seed and Mori et al. In-situ conditions were recreated by first subjecting the samples in laboratory tests to anisotropic stress conditions representing the maximum stress during the geologic history of the deposit and then gradually reducing the pressures to ambient values equal to that existing

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existing in the field. Figure 2-3 shows the test results. The stress ratio required to cause a peak cyclic pore pressure ratio of 100 percent increased by 100 percent. It may be noted that the undisturbed samples were obtained from a heavily overconsolidated deposit having an over-consolidation ratio of about 8.

Ohashi et al. (1976) obtained higher strengths (about double) for undisturbed samples of silty sands as compared with the strengths of "completely disturbed" samples, leading Mori (1978) to suggest that the influence of the proportion of fines (15 to 30 percent silt) might also have a significant effect on the sensitivity of a sand to disturbance (Fig. 2-4).

Horn (1978) presented cyclic load test data (Fig. 2-5) on samples obtained with a Hvorslev fixed piston sampler and on specimens obtained from block samples of dense sands having dry unit weights in the range of 102 pcf to 105 pcf. There is a considerable scatter in the data, and Horn attributes this to the variation in gradation, density, cementation and possibly other factors which should be expected when dealing with undisturbed samples. Nevertheless data from Fig. 2-5 suggests that block samples had a substantially greater cyclic strength than did the fixed piston samples. Possible loosening of dense sands and the loss of the effects of some of the other factors due to the disturbance caused by the fixed piston sampling procedures plus other disturbances due to handling and testing were considered to be the cause of the reduced strength of the fixed piston samples.

Silver et al. (1978) found reconstituted specimens prepared by pluviating Niigata sand through water to be weaker than undisturbed samples by factors of only about 1.16 to 1.22 (Fig. 2-6). Undisturbed

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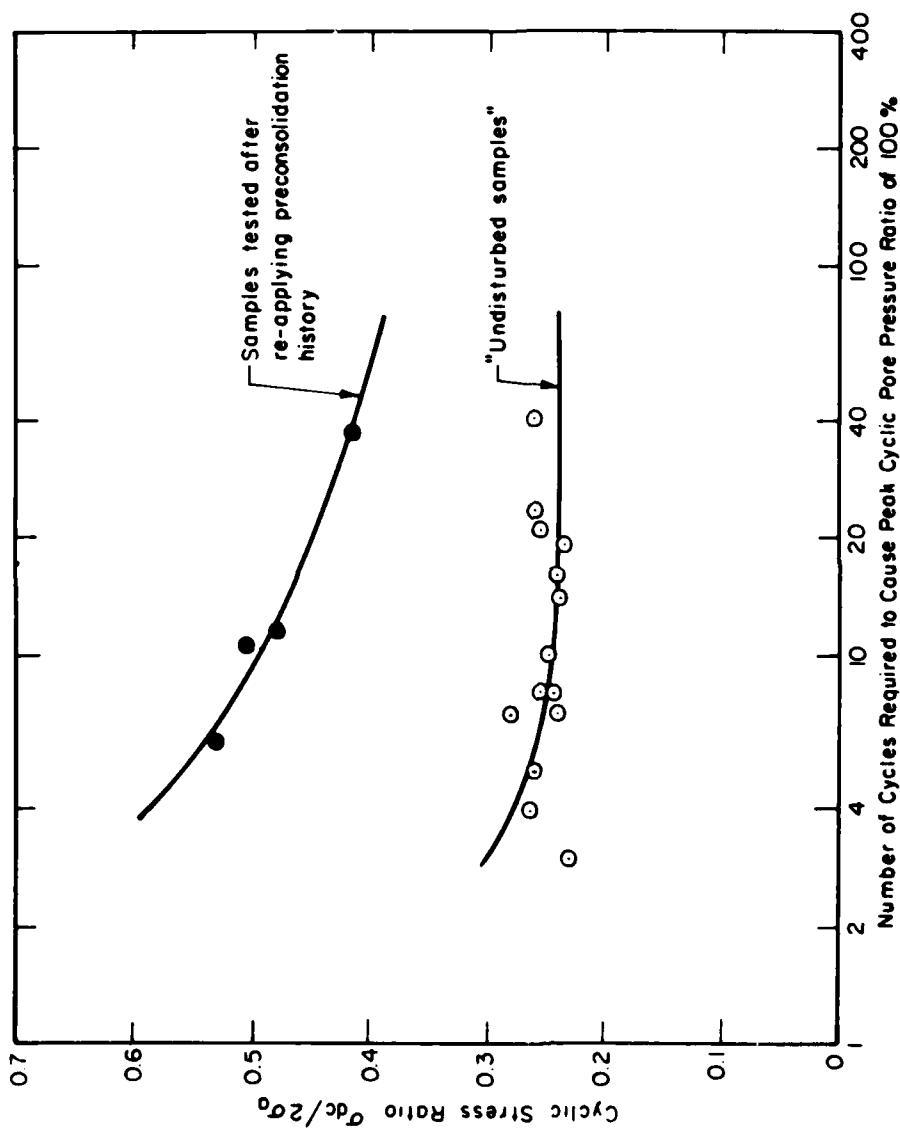
FIG. 2-3 EFFECT OF RECONSOLIDATION ON CYCLIC LOADING CHARACTERISTICS
OF UNDISTURBED SAMPLES

(After Seed, 1976)
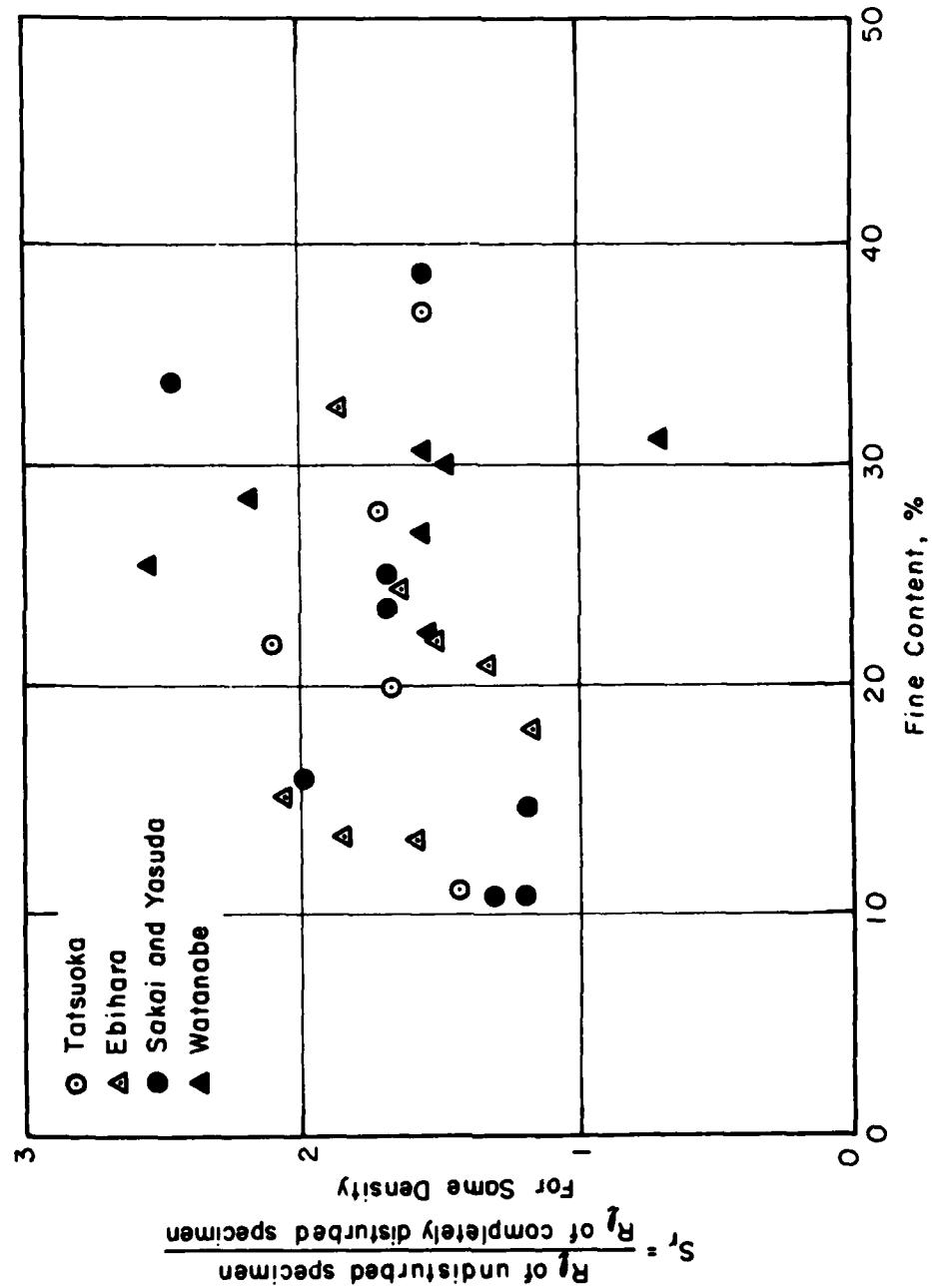
FIG. 2-4 SENSITIVITY OF SILTY SAND
(After Mori, 1978)

Monterey No.0 sand at $D_r = 60\%$
Moist tamping

⊙ Block samples
△ Fixed piston samples

Number of Cycles to Initial Liquefaction

Cyclic Stress Ratio, $\sigma_d / 2\bar{\sigma}_c$

0.5   0.4   0.3   0.2   0.1   0

3   10   30   100
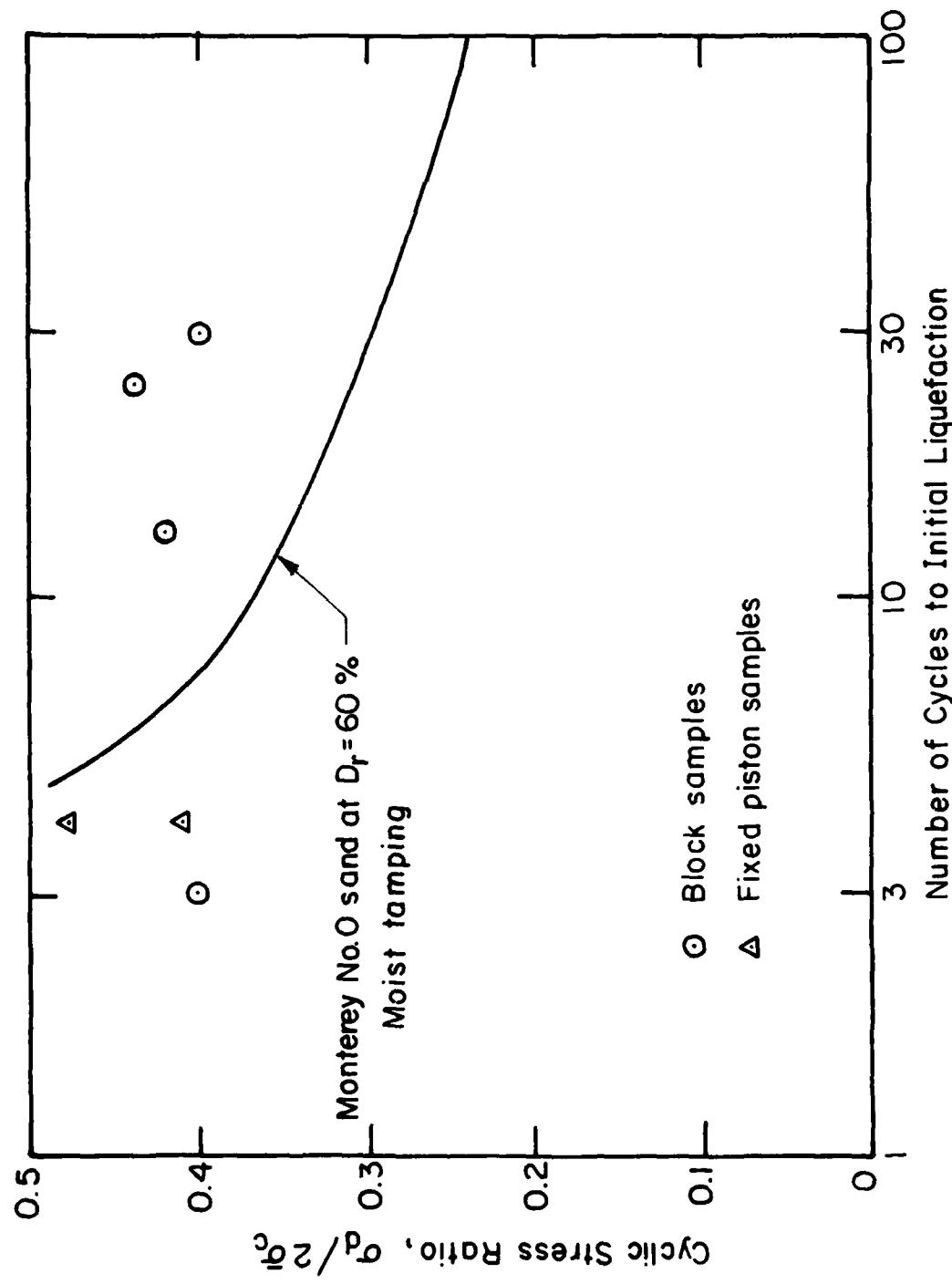
(After Horn, 1978)

FIG. 2-5   COMPARISON OF CYCLIC STRENGTH OF BLOCK SAMPLES AND TUBE SAMPLES OF SAND, BASED ON INITIAL LIQUEFACTION

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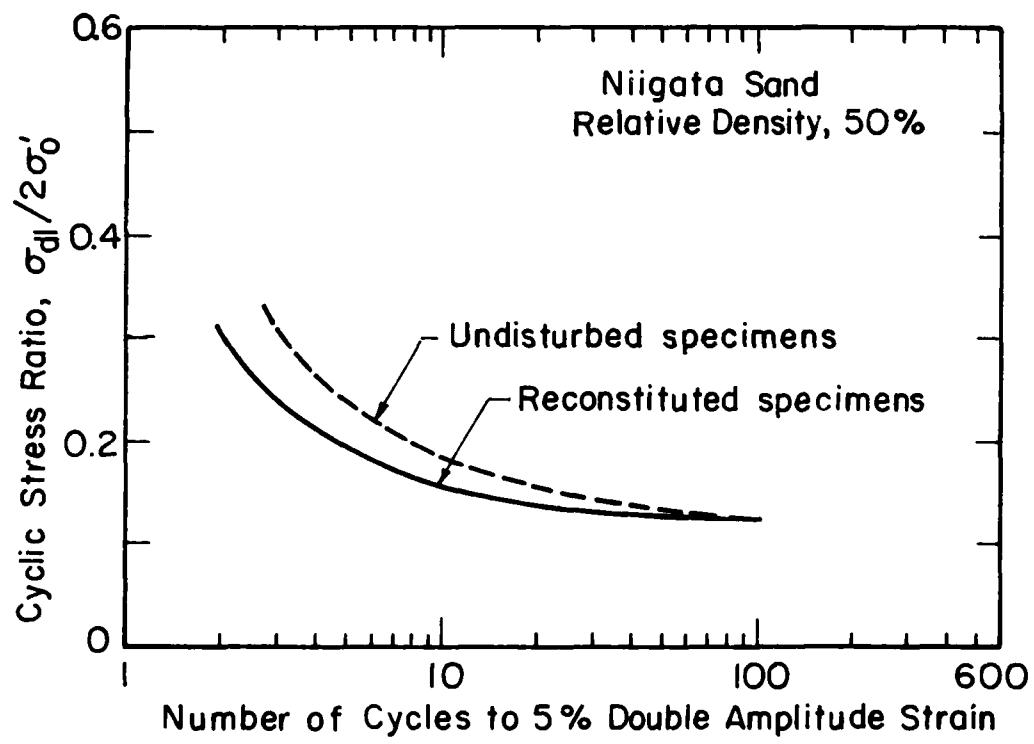
FIG. 2-6 SUMMARY CURVE COMPARING THE CYCLIC STRENGTH AT 50%
RELATIVE DENSITY OF RECONSTITUTED AND UNDISTURBED SAND
SPECIMENS FROM NIIGATA, JAPAN

(After Silver et al., 1978)

specimens were obtained from Niigata by carefully sampling with a large
diameter sampler. On the basis of the test results which indicated that
the cyclic strength difference between reconstituted samples of Monterey
#0 sand prepared by pluviation through water and samples prepared by
moist tamping was about the same as the cyclic strength difference
between reconstituted samples of Niigata sand prepared by pluviation
through water and undisturbed field samples, Silver et al. suggested
that the reconstitution techniques such as wet tamping may better model
in-situ behavior for sands such as that of Niigata.

Salomone et al. (1978) compared cyclic triaxial test data on
samples obtained with Pitcher and Denison samplers to corresponding data
on undisturbed samples obtained using block sampling techniques. Although
on the basis of stress-strain characteristics from static tests, block
sampling technique was found to provide samples which are substantially
less disturbed than tube samples, cyclic strengths were found to be
similar for the variably cemented sands tested. Dry densities of the
Pitcher and Denison samples were typically higher than those of the block
samples indicating perhaps a densification of the Pitcher and Denison
samples. This densification and a relatively stronger cementation of
these sands had probably offset the effect of sample disturbance, produc-
ing similar characteristics for both the disturbed and undisturbed samples.

Espana et al. (1978) also compared cyclic loading characteristics
for samples obtained using the two sampling methods. Both tube and block
samples were tested in accordance with standard cyclic triaxial test
procedures (Silver et al., 1976); laboratory preparation techniques, how-
ever, were also somewhat different for the specimens obtained using tube

and block sampling procedures. Test results indicated relatively low cyclic strengths for samples obtained by the Pitcher tube sampling technique as compared with significantly higher strengths for specimens obtained from hand carved block samples (Fig. 2-7). It may be noted that the average dry densities of about 103.7 pcf indicate a medium dense to dense sand. Espana et al. explained that the existence of small lenses or pockets of fine sand and silty sand and/or the disturbance caused by tube sampling are responsible for the low cyclic strengths of tube samples.

Marcuson et al. (1978) found the strength of reconstituted samples of foundation material from Sardis Dam to be greater than that of undisturbed samples of the same material, i.e., just the opposite of the results cited above. This may be due to the fact that the reconstituted specimens were prepared by the wet tamping method which is likely to yield stronger samples than the in-situ foundation samples. It may be noted that undisturbed specimens were obtained and frozen in the field prior to transporting to the laboratory. For the shell material, the undisturbed and reconstituted strengths were, however, approximately equal. The reconstituted samples of shell material were also prepared by the tamping procedure. It is interesting to note that Sardis Dam is a hydraulic fill dam and the foundation material is an alluvial deposit; thus the tamping method of sample preparation would be expected to yield different fabrics and comparative results.

Summary

Based on the above review of the efforts made to date to evaluate the sampling disturbance in sands, it is reasonable to draw the following conclusions:

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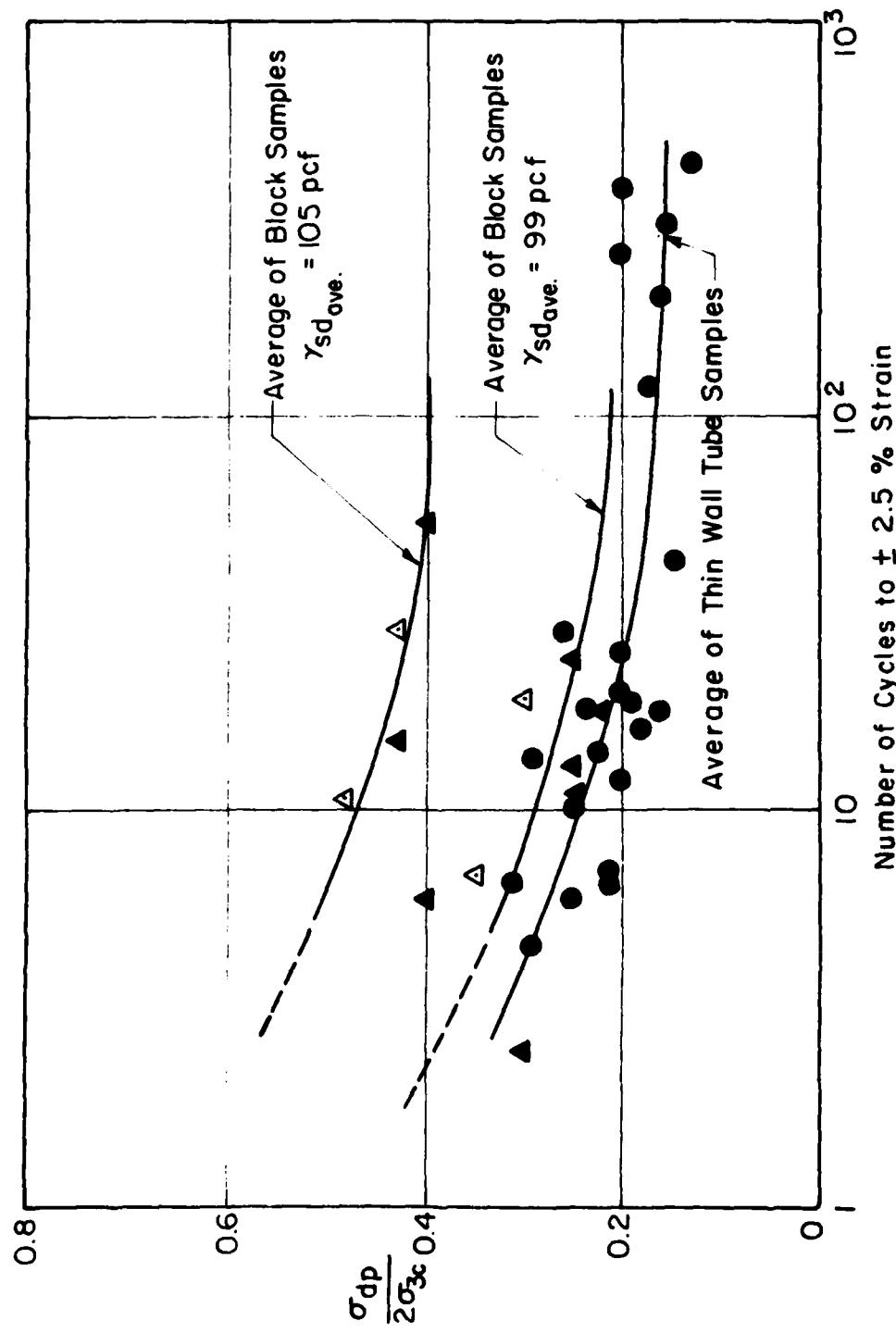
FIG. 2-7 COMPARISON OF THIN WALL AND BLOCK SAMPLES CYCLIC TRIAXIAL STRENGTHS

(After Espana et al., 1978)

1. Laboratory studies conducted by the Corps of Engineers Waterways Experiment Station (1952, 1977) and others, have shown that sampling tends to densify loose sands and cause dense sands to dilate. However, whereas the studies reported in 1952 showed that densification during sampling tended to occur for sands with relative densities less than about 75 percent, recent studies reported in 1977 (Marcuson et al.) indicated that sampling tends to loosen a sand if the relative density is greater than 50 percent. It would appear that the effects of sampling on volume changes for sands with relative densities between 50 percent and 75 percent are not completely resolved. Furthermore, the effect of this sampling disturbance on cyclic loading characteristics is also unclear.

2. In the case of dense sands, block sampling techniques provide samples which are substantially less disturbed than tube samples and, further, their cyclic strengths are usually greater than those of tube samples.

3. In the case of loose to medium dense variably cemented sands, the cyclic strengths of block and tube samples were quite similar.

4. Cyclic strengths of undisturbed samples have generally been found to be higher than those of reconstituted samples prepared to the same density by sedimentation processes in the laboratory.

An important weakness of the previous studies concerning comparative tests on samples obtained by different sampling techniques is that the true field strength is not known, and there are no reliable techniques for measuring the in-situ characteristics. In addition, the unknowns with regard to the degree of loosening/densification and the variations in the sample homogeneity as well as the variability of soil from specimen to specimen tend to further complicate the process of correctly assessing the

quality of the samples. Clearly a reasonable basis for comparison is lacking; and unless sampling is carried out from deposits of known dynamic characteristics, quantitative assessment of the effects of disturbance will remain unresolved.

Accordingly, the facilities at the University of California, Berkeley for testing 12 inch diameter specimens under cyclic loading conditions were modified and used for the purposes of creating deposits of known seismic characteristics. Tube and block samples were then obtained from these deposits in order to evaluate the degree of disturbance and its accompanying effects on the cyclic strength characteristics of the sand. Finally, special procedures such as freezing of the deposits prior to sampling and handling were also investigated in order to determine whether such techniques could maintain the in-situ characteristics so that truly undisturbed samples of sands could be obtained.

CHAPTER 3

EXPERIMENTAL INVESTIGATION OF THE EFFECT OF TUBE-SAMPLING ON CYCLIC STRENGTH CHARACTERISTICS OF SANDS

3.1 General

The questions raised concerning the ability of existing sampling procedures to obtain good quality undisturbed samples of sand and the possible errors introduced due to disturbance during the sampling and handling process, together with the difficulties of assessing correctly the net effect of this disturbance on the actual field strength, have led many investigators to study the effects of sampling on man-made deposits in controlled laboratory environments. Whereas the existence of a small layer, lens or a pocket in a test specimen carved from a block sample can create complexities in evaluating the degree of disturbance, reasonably uniform deposits of sand can be prepared in the laboratory and samples extracted from these deposits. Forerunners in this respect were the engineers at the Waterways Experiment Station (WES).

Over the past three decades WES has conducted various studies to evaluate sampling techniques for determining the in-situ density of sand deposits. In recent years an extensive series of laboratory tests has been conducted using a "stacked ring" container to study the influence of tube sampling on sample density (Marcuson et al., 1977, Cooper, 1976). The Hvorslev-fixed-piston sampler was used in the sampling procedure. On the basis of density measurements, these studies indicated that (1) high quality undisturbed samples of sand can be obtained using a fixed piston sampler and drilling mud, (2) that this and the sampling procedure yields

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very good samples of medium sand but tends to densify loose sands and loosen dense sands. This confirmed the general results of earlier studies (1952) although the different investigations indicate different relative densities, ranging from about 50 to 75 percent, at which loosening occurs during the sampling process. Marcuson et al. further suggested that a more meaningful assessment of sampling accuracy could have been made if it were possible to achieve more uniform density control during the studies.

Whereas the WES studies throw significant light on the effect of sampling disturbance on changes in density, a direct assessment of the effect of disturbance on the cyclic strength characteristics was not made. The only study of this type conducted to date is that by Mori, Chan and Seed (1978), who investigated the influence of driving or pushing a sampling tube into sand beds, artificially prepared in the laboratory, utilizing the large shaking table used by DeAlba (1975). The bed of sand had known characteristics and had been given a known prior strain history. The confining pressure was removed prior to sampling and the sample length was 4 inches. No change in density was observed but in spite of the great care taken in sampling and handling, the test results indicated that for the sand investigated (Monterey #0), virtually all of the effects of prior strain history were lost (Fig. 3-1). Mori et al. attributed this to (1) reduction of confining pressure, (2) disturbance during sampling, and (3) further disturbance due to sample handling in the testing procedure. It was found that merely the reduction of confining pressure, thus simulating perfect sampling, seems to reduce the beneficial effects of prior seismic history to about 35 percent of their original magnitude (Fig. 3-2).
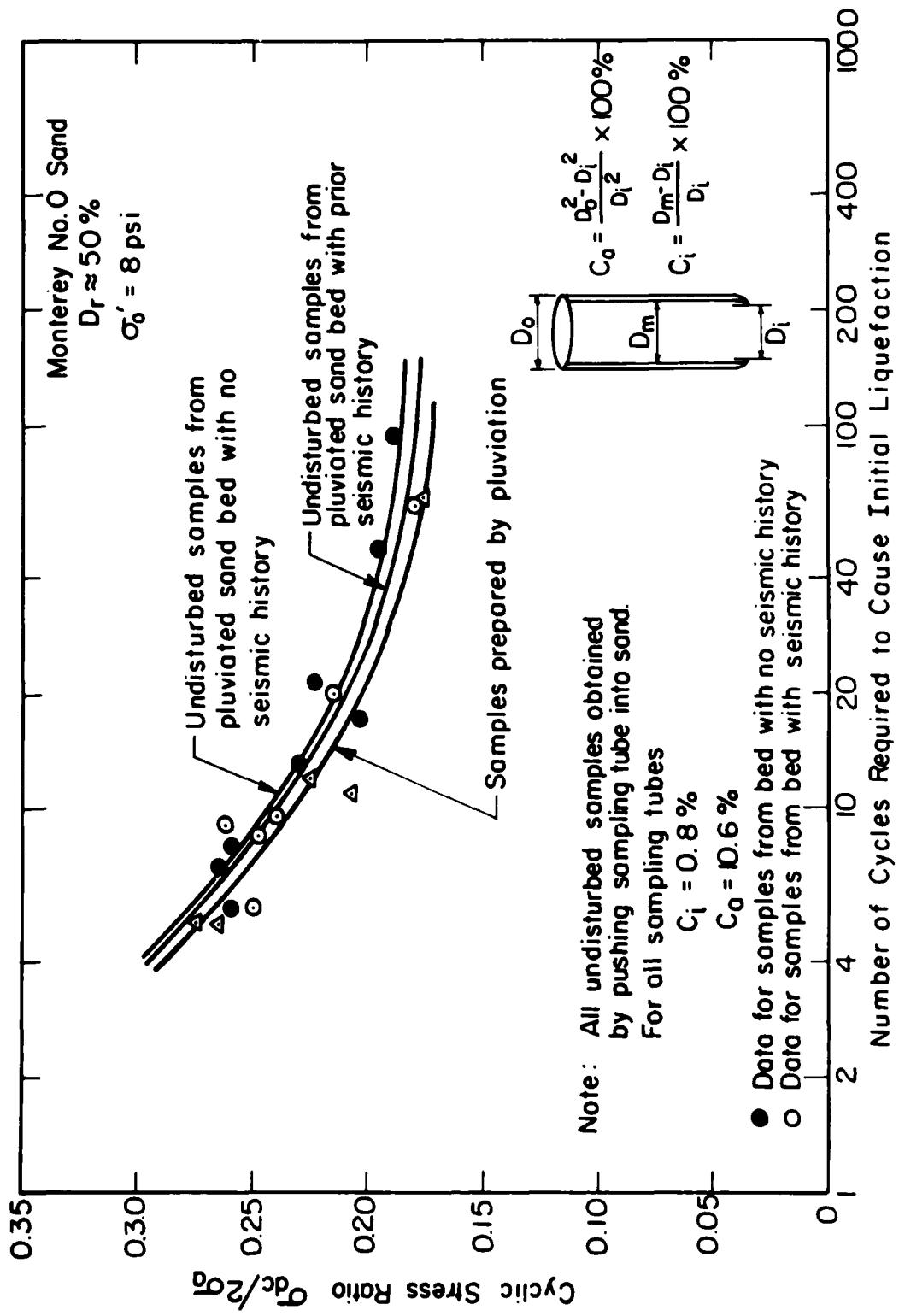
FIG. 3-1   EFFECT OF SEISMIC HISTORY OF SAND BED ON LIQUEFACTION CHARACTERISTICS OF UNDISTURBED SAMPLES

(After Mori, Seed and Chan, 1977)

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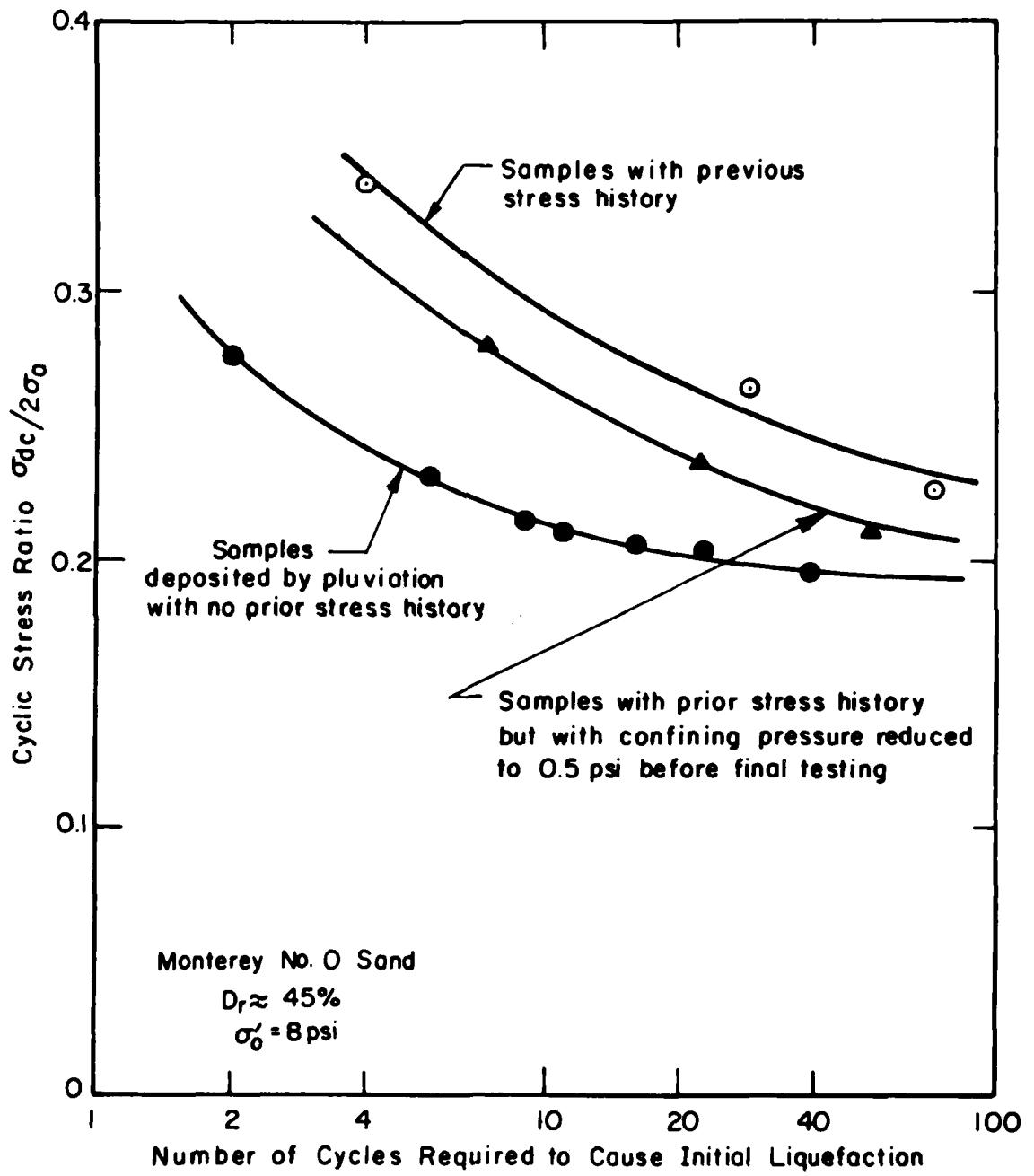
FIG. 3-2 EFFECT OF STRESS REDUCTION ON LIQUEFACTION CHARACTERISTICS
OF SAND WITH PRIOR STRESS HISTORY

(After Mori, Seed and Chan, 1977)

Since Mori et al. sampled from beds of sands which had their con-
fining pressures removed prior to sampling, it is difficult to evaluate
the nature and degree of disturbance due to the tube insertion alone.
Accordingly this particular source of sample disturbance and its accom-
panying effects have yet to be fully resolved. For the investigation
discussed in this chapter existing facilities at the University of
California for testing 12 inches diameter specimens under triaxial cyclic
loading conditions were modified and used to determine the effects of
sampling from deposits having a known seismic history while the confining
pressure was continuously maintained, thereby simulating currently-used
methods of sampling of sands from actual deposits. Following a brief
description of the experimental set up and test procedures, the results
of the tests will be presented and discussed.

3.2 Description of the Testing Equipment

(a) The 12 Inch Diameter Cyclic Triaxial Equipment

The cyclic triaxial apparatus capable of testing 12 inch diameter
samples was used in this study; the apparatus has been described in detail
by Wong (1971). The apparatus uses a standard MTS closed loop system.
There are two kinds of controls, i.e., 'load' and 'stroke' control and two
commands, one through set-point which is manually adjusted and the other
through a data track programmer. "Load Control" was used for this
investigation. The data were recorded by Sanborn recorders and occasionally
checked by digital voltmeters. For a detailed description of the apparatus
including the MTS and the Sanborn recording systems, the reader is referred
to Wong's thesis.

For the present investigation it was necessary to make a major modi-
fication to the cap of the test specimen to allow access to the sample for

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undisturbed sampling while still maintaining the confining pressure on the specimen. This also required a redesign and relocation of the load cell to the base in order to overcome the problem associated with the calibration for the differential pressure across the load-cell originally provided with the 12 inch diameter machine. Figure 3-3 is a sketch of the cap showing the piston sampler passing through it. A system of O-rings, one between the outside of the brass sampler tube and the inside of the walls of the opening in the cap and another O-ring between the locking head and the outside of the walls of the opening, prevented the escape of the air and hence any loss of confining pressure from the chamber. The seal of the piston whose rod is locked and held in position by the sampler-pushing device prevents the pore water from escaping. The system worked very satisfactorily and it was possible to sample against back pressures as high as 3 kg/cm^2 without any leakage or loss of chamber or back pressure.

(b) The Sampling Equipment

In order to push the sampler smoothly into the 12 inch diameter sample at a controlled rate, a hydraulically operated mechanism was designed and assembled. Figure 3-4 shows the sampling device when it is set on the top of the triaxial chamber and is ready for use. The rate of penetration of the sampler was controlled by the hydraulic pressure and by the rate of flow of oil into the pressure cylinder.

(c) The Thin-Wall Sampler

A thin-walled fixed piston Hvorslev type sampler was used to obtain undisturbed samples. The sampling tube was made from seamless hard drawn brass tube 3 inches in outside diameter with 1/16 inch wall thickness. The thin-wall sampler had a sharpened cutting edge which was kept straight from

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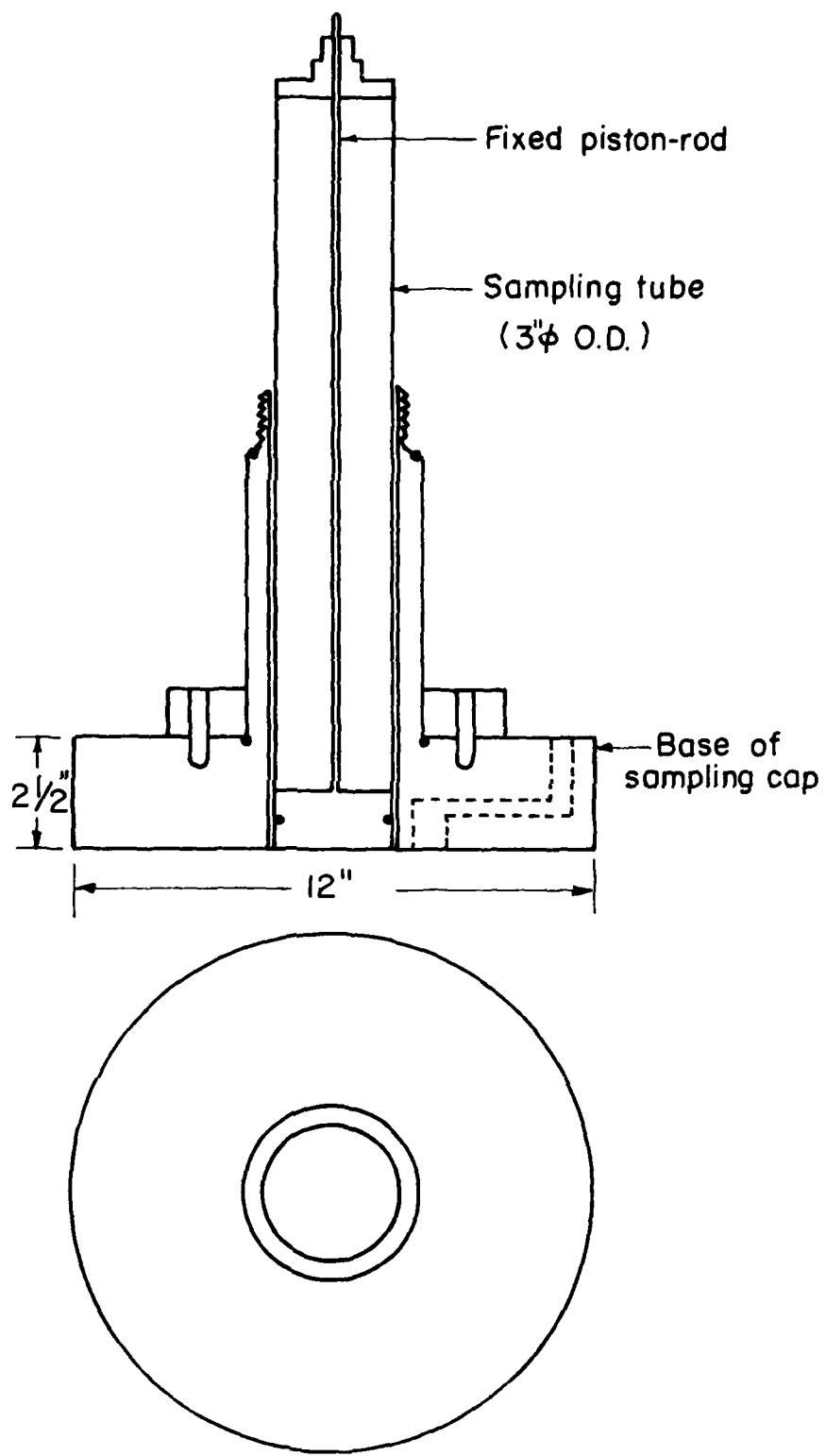
FIG. 3-3 SAMPLING TUBE WITH HVORSLEV-TYPE FIXED PISTON
SAMPLER SET IN IT

Piston rod (remains fixed)

Sampling rod

Hydraulically operated system
for pushing sampling base

Sampler head

Sampling tube

Steel chamber

Rigid reaction
for use in cyclic loading
of 12"diam. sample

Sampling cap

Sample

12"diam.

Pressure
Actuator
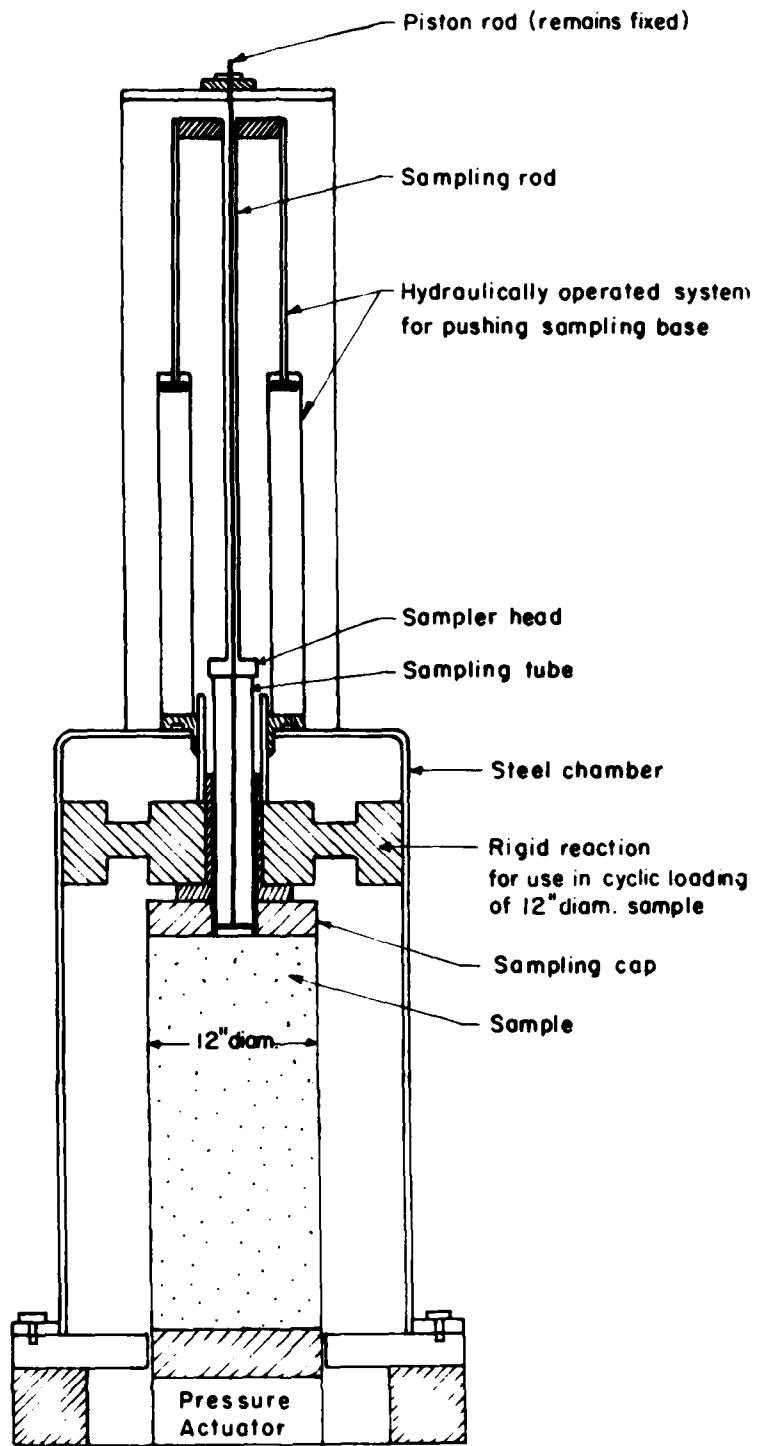
FIG. 3-4 SCHEMATIC ARRANGEMENT OF SAMPLING DEVICE SET ON TOP
OF TRIAXIAL CHAMBER

inside so that the inside diameter of the tube and that of the cutting edge were the same, i.e., no inside clearance was provided. The inside diameter of the tube was 2.875 inches. The area ratio was thus equal to 8.9% which is well below the minimum recommended by Hvorslev to achieve good results. The total length of the sampling tube was 19 inches. A locking head at its top end connected it to the sampling rod and a piston plug at the bottom end of the tube sealed the pore pressure. The piston rod was guided through the head and through the sampling rods to the top of the sampling device and was kept in locked position for fixed-piston sampling.

The piston rod, the tube and the sampling rods were kept in a locked position to act as a part of the 12 inch diameter specimen cap during the time the specimen was being subjected to cyclic loading.

3.3 Description of the Sand

Monterey #0 sand was used in this investigation. This sand has been extensively tested for studying various characteristics which are now well documented in the literature. Also experience has shown that the problem of layering usually encountered with well graded soils during sample preparation is eliminated when uniformly graded sands such as Monterey #0 sand are used. The sand has the following characteristics.

1. It is a uniform medium sand passing the No. 30 sieve and retained on the No. 50 sieve.

2. It has a uniformly coefficient of about 1.5.

3. The mean grain size is about 0.4 mm.

4. The length to width ratio of individual grains (after Mahmood, 1973) is about 1.4.

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5. Quartz and colored feldspar are the predominant minerals.

6. The maximum and minimum densities are 106.9 pcf and 89.1 pcf, respectively.

Although Monterey #0 is a specially processed sand and the grain sizes are generally uniform, the maximum and minimum densities have been found to vary somewhat from one stock-pile to another and even within a given stock-pile. In order to check the uniformity of the sand in the source stock-pile for this investigation, maximum and minimum density tests were made on batches of sand obtained from several locations within the stock-pile. The batches of sand were obtained from the top, middle, bottom and from a few random locations within the stock-pile. The differences in the maximum and minimum density values from one batch to another were found to be minimal and led to changes in relative density of the order of 2 percent. However, near the end of the testing program, as the bottom of the stock-pile was reached, the sand seemed to have more fines. Additional maximum and minimum density tests made at this stage showed changes in the values of relative density of 2 to 4 percent. The cyclic load test involving seismic history effects showed similar behavior.

The maximum and minimum densities were determined in accordance with the ASTM D 2049-69 procedure. Check tests on maximum and minimum density values of sands from different locations were, however, made using an efficient and slightly modified version of a Japanese method.

A typical gradation curve for the sand is shown in Fig. 3-5.

3.4 Description of the Method of Sample Preparation

For the study of soil sampling effects, 12 inch diameter samples of uniform density which were reproducible from test to test were required.

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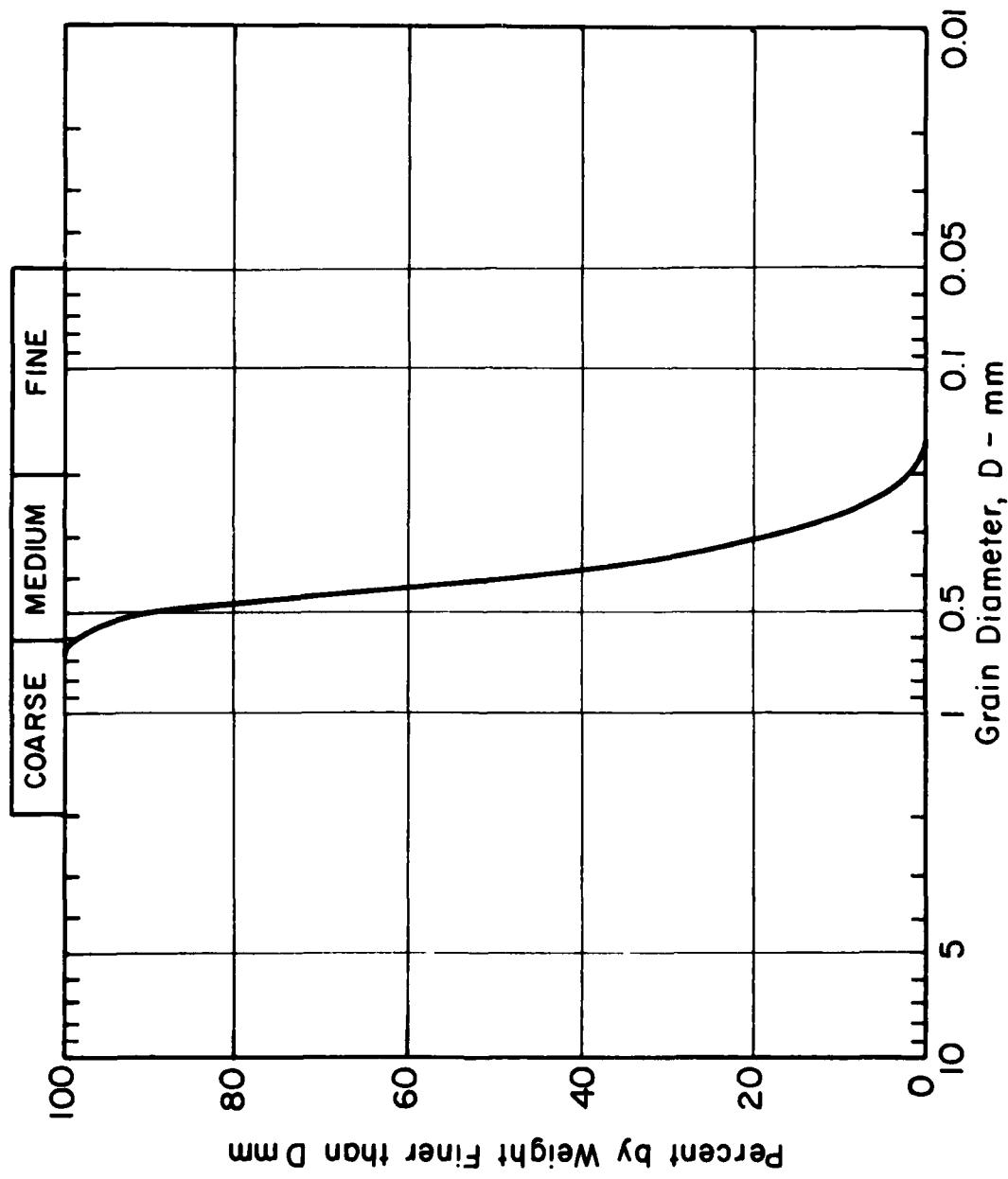
FIG. 3-5 GRADATION CURVE FOR MONTEREY NO. O SAND

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Whereas many sample preparation techniques are available, the size of the sample and the density at which a sample is to be prepared can greatly influence the choice of the method of sample preparation. The preparation of a homogeneous specimen 12 inches in diameter and about 27 inches in height is not an easy task. The pluviation method of placement still offers the most convenient procedure. It permits placing large quantities of sands quickly and easily. In addition, it is closer to the manner of placement of natural deposits of sands than compaction methods. The method consists of allowing a free fall of sand through an opening or a nozzle into a mold representing the shape and size of the desired specimen. Mulilis et al. (1975) have explained this method of pluviation through air or water in detail. Pluviation of dry sand through air was used for this investigation. However, the method as originally used by Pyke (1973) or Mulilis (1975) was modified in that as the sand dropped from the nozzle or an opening in the base of the container, it was made to fall through a funnel into a series of sieves which intercepted and broke up the concentrated jet-like stream of the sand and created a uniform rain of sand as it emerged through the last sieve. The funnel which first receives the sand from the reservoir can be selected with a predetermined nozzle size to achieve the desired density. This arrangement of the sieves and the funnel devised to create a uniform rain of sand will henceforth be called the "multiple-sieve pluviation system" (Fig. 3-6). Since the diameter of the falling column of rain of sand is about 3 inches, the multiple-sieving system is rotated slowly to cause the sand to be evenly distributed over the surface of the 12 inch diameter specimen.

Specimen preparation involved a continuous pouring of the sand into the mold while the multiple-sieving system along with the reservoir were

Sieve A'
Sieve A
1"
Sieve B
1"
Sieve C
1"
Sieve D
1"
Sieve E

0.1"

0.1"

Sieve A'

0.3"

0.3"
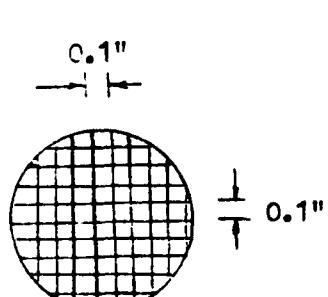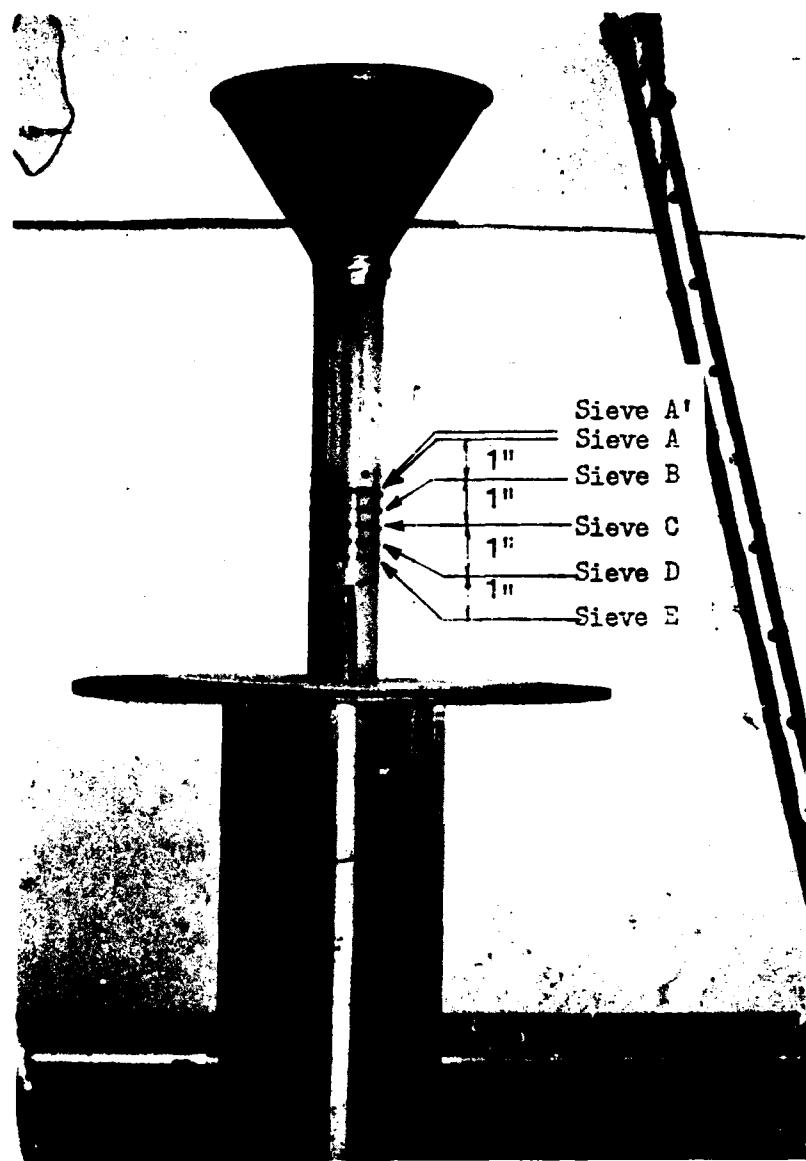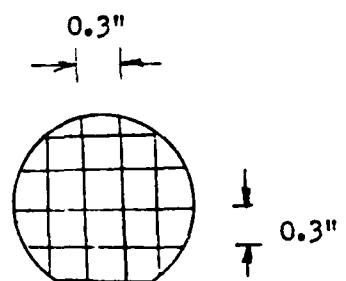
Sieve A , B , C , D, E

FIG. 3-6 MULTIPLE-SIEVING PLUVIATION SYSTEM

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raised up gradually but intermittently every 38 seconds, a predetermined time interval which allowed a lift of about two inches to be formed, thus permitting a variation of not more than 2 inches in the height of fall at any time during the specimen preparation procedure. The density produced using this method is dependent on the following factors:

1. The Size of the Nozzle Opening. It was found that the relative density of the poured sand is very sensitive to the size of the nozzle opening of the funnel. The larger the size of the nozzle, the more intense is the rain of sand and the lower is the density attained (Kolbuszewski, 1948, and Mulilis, 1975). After several trials the right size of nozzle was determined to achieve the desired relative density of 60 percent.

2. The Height of the Fall of Sand. The density of the sample is influenced by the height of fall of the sand from the point where it emerges from the multiple sieving system to the surface of the sand in the mold. A separate set of tests was conducted to study the effect of the height of all. A mold 11.4 inches in diameter and about 2.5 inches in height was used for this purpose. Sand was deposited in this mold by raining through the multiple sieving system. For each trial a different height of fall was set and the weight of the sand deposited in the mold was determined. It may be noted that for a height of fall of 32 inches or more the density achieved varied only slightly with increases in the height of fall. During the actual sample preparation, the height of fall was kept at 38 inches for each 2 inches of lift.

3. The Speed of Rotation of the Multiple-Sieving System. The sieving system was rotated in a circular motion and it was found, as did Mulilis (1975), that a faster speec of rotation results in a higher density. The speed of rotation required to produce the desired density was achieved after a few trials and after a little experience it was possible to reproduce about the same density consistently.

The relative density variation within a given specimen was on the order of 3 to 5 percent as checked by the measurements of the densities of cored samples from different locations of a frozen specimen.

3.5 The Testing Program

Utilizing the equipment and the method of sample preparation described above, four different series of tests were conducted to study the effect of tube sampling on the cyclic loading characteristics of Monterey #0 sand which had previously been subjected to a predetermined strain history to change its normal cyclic loading characteristics without changing its density. The first three series of tests were conducted on 12 inch diameter specimens, whereas the fourth series of tests was made on 2.8 inch diameter samples which had been sampled from 12 inch diameter specimens.

The objective of each of the test series was as follows:

1. Test Series 3-A was performed to establish the cyclic load characteristics of a freshly deposited sand at a relative density of 60 percent.

2. Test Series 3-B was performed to establish the cyclic load

characteristics of the same sand specimens used in Series 3-A

after they had been subjected to a known series of strain history

effects following the procedures used by Seed et al. (1975).

3. <u>Test Series 3-C</u> was performed to obtain samples by pushing the

tube sampler (Hvorslev piston-type) into the 12 inch diameter

specimens which had previously been given the same seismic

history effects as were the samples under Test Series B.

4. <u>Test Series 3-D</u> was performed to establish the cyclic load

characteristics of the 2.8 inch diameter samples extruded from

the tube samples which had been obtained under Test Series C.

Test Series A and B established the basic characteristics of the

sand and the lines on a typical stress ratio versus number of cycles plot

describing these relationships are hereafter referred to as the "virgin"

and "strain history" lines respectively. These relationships provide the

framework or the basis for evaluating the effect of disturbance due to

sampling.

In addition to the above test series, studies were undertaken to

evaluate the effects of frequency and sample size on the cyclic strength

characteristics of 2.8 inch and 12 inch diameter samples prepared by

using identical methods of sample preparation. These studies confirmed

the conclusions of Wong (1972) and Mulilis (1975) that the frequency and

size effects for the two sizes used and for the type of the sand used in

this investigation are negligible.

3.6 Test Procedures and Test Results

In this section a brief description of the test procedures used for

each of the test series and the results thus obtained are presented.

The method of sample preparation for each of the test series described in this as well as in subsequent chapters was the same and is described primarily in this chapter.

The procedure used for sample preparation set up is a two person operation. One person rotates the multiple-sieving system while the other person controls the height of the fall and raises the reservoir as the sample builds up. After some practice the whole operation (Fig. 3-7) can be effectively synchronized. Calibrated markings, every 2 inches of height on the side panel of a fork lift and a stop watch to control the rate of rise, and in addition an intermittent check on the height of fall by actual measurements, provide an effective control on the height of the fall. A continuous visual inspection of the surface of the sample through large holes in the base of the multiple-sieving device ensures even spreading and rise of the sample surface during the pluviation process. After the sample is prepared to the desired height, the operation is stopped and the surface of the sample is levelled by carefully scraping the sand with a straight-edge scoop. The sample is now ready to receive the cap which is different for different test series.

Test Series 3-A

After the sand had been poured into the mold to a height of about 27 inches, the surface of the sample was levelled and an ordinary cap similar to the one used for routine triaxial testing was set on top of the sample surface. The top drainage line was then connected to the cap and a vacuum applied. The remaining procedure from removal of the sample preparation mold to saturation and cyclic testing is similar to that described by Mulilis (1975) for pluviated samples. For the Monterey #0

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HOISTED BY OVER HEAD CRANE

RESERVIOR OF SAND
(CAPACITY 400LBS.)

SAND

MARKING FOR 2" LIFT

MULTIPLE-SIEVE-
PLUVIATION DEVICE

PLATFORM
RISES
GRADUALLY

FORKLIFT FOR RAISING
THE PLATEFORM

HEIGHT OF
FALL

PLUVIATED
SAND
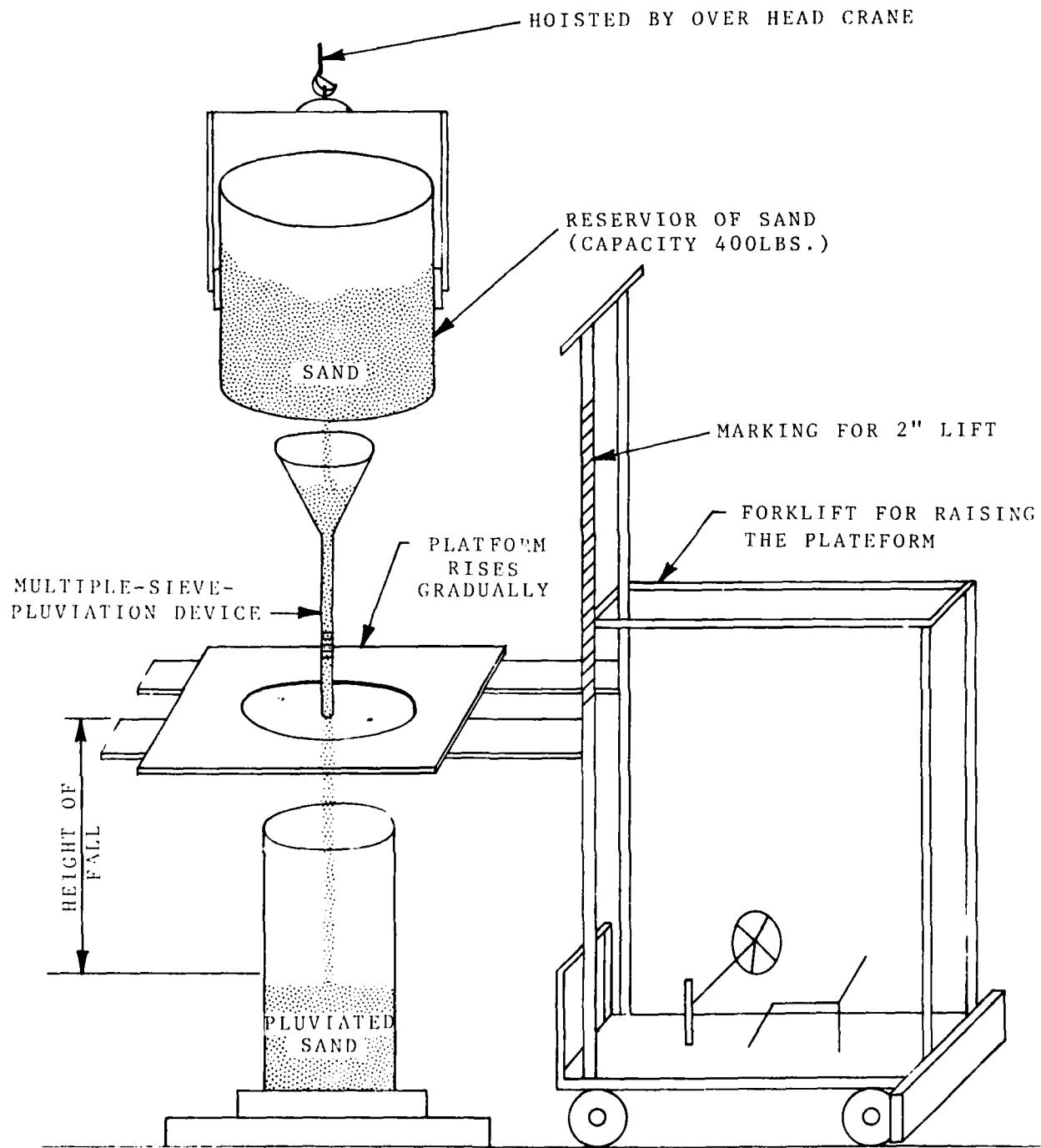
FIG. 3-7 SET-UP FOR SAMPLE PREPARATION

sand used in this investigation it was possible to achieve 'B' values of 95 percent or greater without the use of carbon dioxide. The back pressure, however, was usually 2 kg/cm^2 or more.

Each sample was subjected to an effective confining pressure of 0.56 kg/cm^2 (8 psi), which is equivalent to that produced at a depth of 15 feet with a ground water table at about 4 feet below the ground surface. The sample was then cyclically loaded until the induced pore pressure ratio reached a value of 100 percent and significant strains developed. Figure 3-8 shows the results of such tests. Since these samples had not been subjected to any prior shaking or any other pre-straining before they were cyclically loaded to 100 percent pore pressure ratios, the graph showing the relationship between the cyclic stress ratio and the number of cycles required to produce this condition is referred to as the virgin line.

Test Series 3-B

Identical samples to those described under Test Series A were prepared. After complete saturation, the samples were subjected to seismic history effects. As reported by Finn et al. (1970) and Seed et al. (1975) application of a series of small strains representative of small earthquakes, each followed by a complete dissipation of the excess pore water pressures, will greatly increase the resistance of a deposit to the development of liquefaction or 100 percent pore pressure ratios under a larger earthquake. To simulate these conditions each sample was subjected to the effects of six small earthquakes, each represented by 10 cycles of loading at the low stress ratio of 0.18 with excess pore water pressure being drained after each series of cyclic stress applications.

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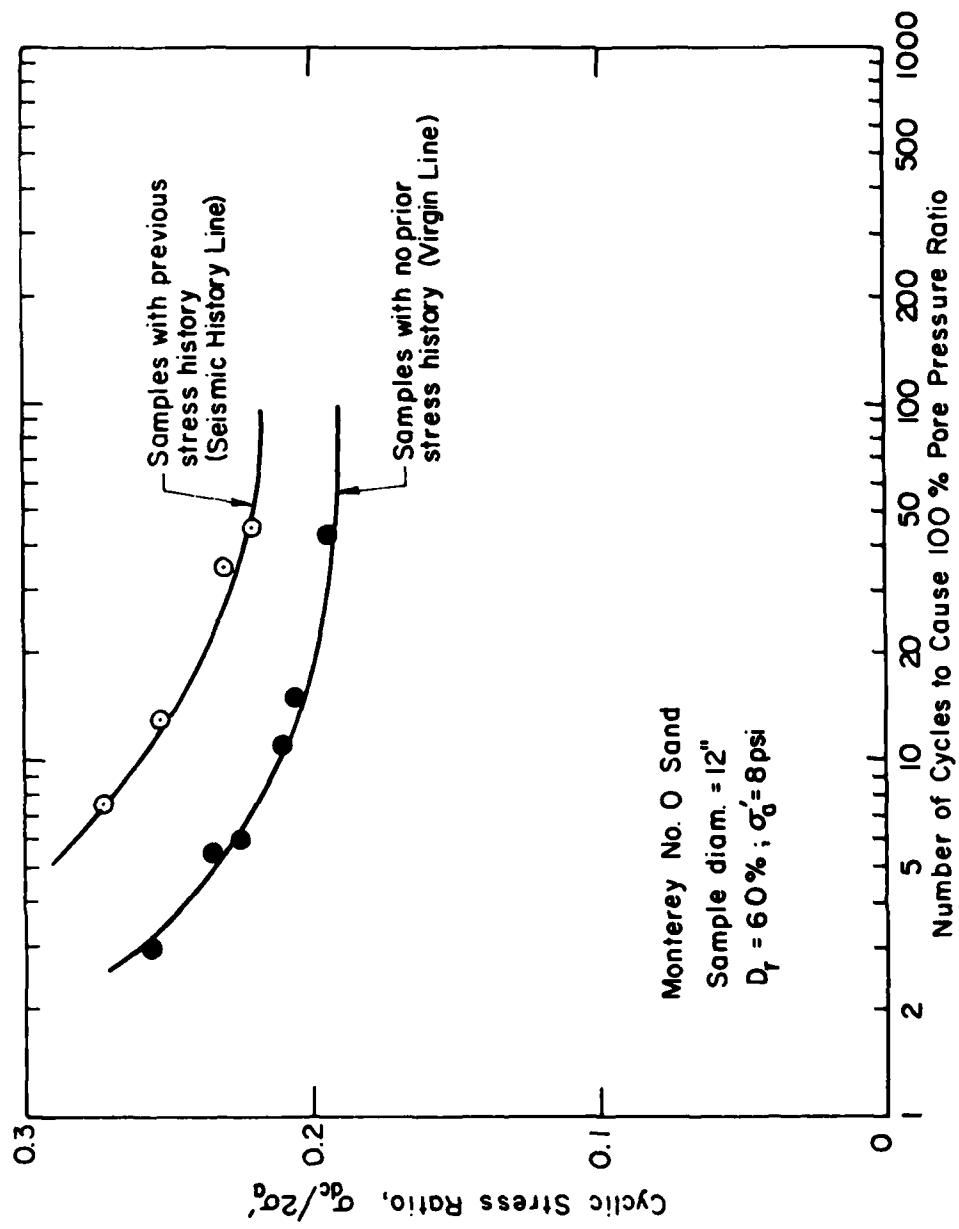
FIG. 3-8 CYCLIC LOADING CHARACTERISTICS OF PLUVIATED SAMPLES OF MONTEREY NO. O SAND OBTAINED USING 12-INCH DIAMETER SAMPLES

At the end of the full series the relative density of the specimen had increased from its initial value of 60 percent to about 60.2 percent, an extremely small change. Finally, the samples were subjected to cyclic stress ratios until they developed a condition of 100 percent pore pressure ratios and significant strains. Figure 3-8 shows the results of these tests. The graph showing the relationship between the cyclic stress ratios and number of cycles required to produce a pore pressure value of 100 percent for samples which had been subjected to seismic history effects is referred to as the strain history line.

Test Series 3-C

Utilizing the same method of sample preparation as for series A, samples were poured to the same relative density (60 percent) as were those for Test Series A and B. After the surface of the sample had been levelled, the "sampling cap" which had the sampling tube already set in it, was placed on the surface of the sample. Application of the vacuum, sealing of the sample and setting up of the triaxial chamber were carried out following the usual procedures. However, before applying the cell pressure, the sampling equipment was installed on top of the chamber (Fig. 3-4) and the piston rod and sampling rod were locked in position so that no relative movement of the piston plug or sampling tube could occur during the application of back pressure and subsequent cyclic loading. The whole system worked very well.

The 12 inch diameter sample was then subjected to the same seismic history effects as were the samples in Test Series B. At the end of the application of the strain history effects these samples were not cyclically loaded to 100 percent pore pressure ratios. Instead a sampling operation

was carried out. With the piston rod locked firmly in position, as in fixed piston sampling, the sampling tube was unlocked and pushed into the specimen at a rate of 2 to 3 inches per second. The cell pressure and back pressure were kept unchanged during this process so that the sampling was carried out while the specimen remained under the effective confining pressure of 8 psi. The drainage lines were kept open during sampling and the amount of water drawn in or out of the specimen was noted; however, it was always the case that water drained out of the specimen as the tube was pushed in. The amount of water pushed out was about the same each time and was on the order of 100 cc. About 13 to 14 inches of the tube was pushed into the 12 inch diameter sample for each test.

At the completion of the pushing stroke, the sampling rod was locked in position. In order to minimize disturbance effects, the sampling tube containing the sample was not pulled out, but instead the specimen was put under vacuum to allow access to the specimen by dismantling the triaxial chamber including the sample pushing device so that the sampling tube could be excavated from the specimen. A rigid support system was designed to prevent rocking or vibration of the tube during excavation. The membrane surrounding the 12 inch diameter specimen was carefully pulled down to expose the specimen (Fig. 3-9). It may be noted that the specimen retained its shape because of the capillarity and no sloughing or fall off of sand occurred. The soil surrounding the sampling tube was hand trimmed and excavated to the bottom of the tube at which stage a thin stainless steel plate was carefully inserted under the

FIG. 3-9   SET-UP FOR RETRIEVING TUBE-SAMPLES

sampling tube. The tube was then freed from the cap and was gently hand carried to the extruding device.

Test Series 3-D

This series of tests involved extruding of the 2.8 inch diameter samples, then preparation for cyclic triaxial tests and finally cyclic load testing of the extruded samples.

Extruding and setting up of a saturated or partially saturated sand specimen is an extremely difficult operation; and if disturbance effects are to be avoided, special precautions must be taken. Saturated samples extruded from thin-wall tubes often tend to slump or sometimes even fail to stand up. A procedure similar to the one used by Mori (1976) was designed to overcome these difficulties. Undisturbed samples thus extruded and set up in the triaxial machine were then saturated under an effective confining pressure corresponding to the one used for the large diameter specimen (0.56 kg/cm^2) and finally subjected to cyclic loading to determine their cyclic loading characteristics. Figure 3-10 shows the test results for these samples. The stress ratios required to cause pore pressure ratios of 100 percent for these extruded samples were found to be somewhat higher than those of the strain history samples. However, it was also found that the samples had increased in density during the sampling operation, with the average increase in relative density being on the order of 6 percent. Is it then that the previous seismic history effects have not been completely lost? How much has the increase in density contributed to the recorded strength of extruded samples? In order to resolve these questions, virgin 12 inch diameter specimens were prepared as explained in Test Series A and 2.8 inch diameter
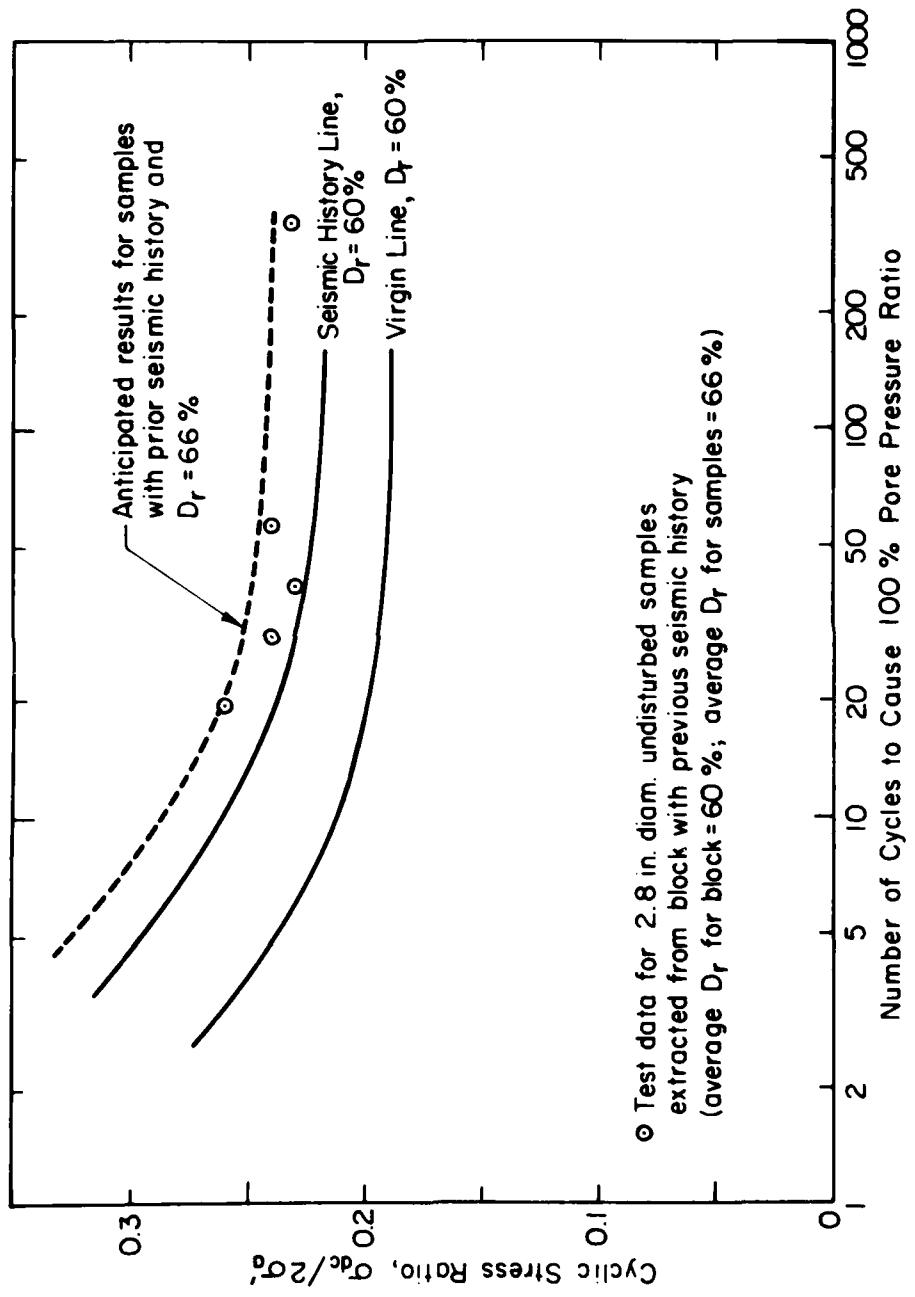
FIG. 3-10 EFFECT OF PUSH TUBE (HVORSLEV FIXED PISTON) SAMPLING ON CYCLIC LOADING CHARACTERISTICS OF SAND WITH PRIOR CYCLIC STRESS HISTORY

samples were sampled from these. The procedures for sampling, handling, extruding and testing were the same as described under Test Series C and D. The test results still indicated a strength slightly lower than the "strain history samples" (Fig. 3-11) but the average relative density of these samples had increased by about 10 percent. The anticipated cyclic strength characteristics of pluviated samples at a relative density of 70 percent are also plotted in Fig. 3-11 and it may be seen that the measured characteristics can be explained simply as the result of the densification during sampling. Applying this same procedure to the "strain history samples" leads to the conclusion that the measured strengths are somewhat less than those corresponding to a relative density of 66 percent, indicating some small loss of the strain history effect in the sampling procedure.

Discussion

The studies reported above have demonstrated that while the primary concern with regard to the sampling of cohesionless soils has been on the change in density, the associated change in the nature of grain-to-grain contacts can also be significant. Loosening or a densification of sand during sampling involves relative movements between sand grains. If the density change is small and has involved loosening resulting in partial or complete rupture of cementing effects, the increased resistance due to prior seismic history is expected to be partially or completely lost. The nature of the cementation and the type of the soil can also influence the degree of this loss. On the other hand, if densification is involved, the resulting strength will be determined by the combined effect of the increase in resistance due to
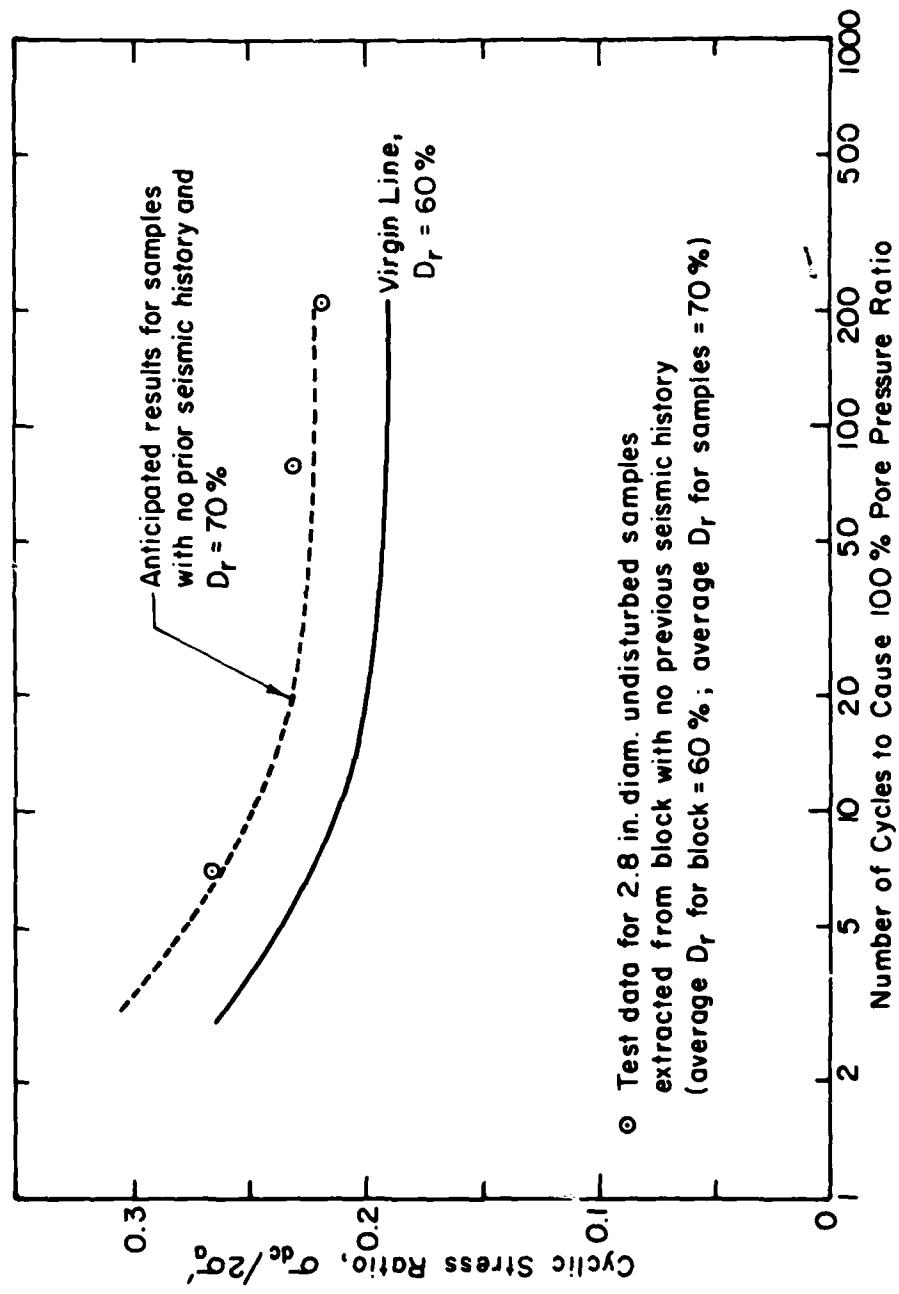
FIG. 3-11 EFFECT OF PUSH TUBE (HVORSLEV FIXED PISTON) SAMPLING ON CYCLIC LOADING CHARACTERISTICS OF PLUVIATED SAND

increase in density and associated straining, loss of resistance due to
the breaking of the cementing (or grain-to-grain) bonds and the loss in
resistance due to strain history effects. As stated earlier, the type
of the soil and the nature of the cementation, including the in-situ
density and the change in density are the important parameters which would
influence the degree of disturbance and hence the final cyclic strength
of an undisturbed sample obtained by push tube sampling techniques. While
interpreting laboratory test results, the importance of taking into account
these parameters, judgmentally or otherwise, cannot be overemphasized.

CHAPTER 4

EXPERIMENTAL INVESTIGATION OF THE EFFECT OF BLOCK-
SAMPLING ON THE CYCLIC STRENGTH CHARACTERISTICS OF SANDS

4.1 General

It is generally believed that a block sample will more closely
meet the requirement of a truly undisturbed sample than would a sample
obtained by any other method currently available. The method of block
sampling involves isolating a column of soil by excavating the sur-
rounding material, surrounding it with a section of tubing or a square
box and finally cutting it free. Block samples are mostly taken from
the base of test pits or exploratory shafts or trenches. The method can
be successfully used in all soils provided the true or apparent cohesion
is large enough that a soil column can be isolated. Sometimes a com-
bination of advance trimming and block sampling by carefully pushing a
cylindrical tube over the trimmed soil column before trimming to a
further depth is used.

When compared to tube samples, block samples have the disadvantage
of requiring a significantly large amount of excavation and trimming, but
the disturbance caused by displacement of soil during driving or pushing
a sampling tube into the ground can to a large extent be eliminated by
block sampling techniques. However, the disturbance associated with the
stress change due to excavation of the test pit or the lowering of the
ground water level if the excavation is carried out below the ground water
level, cannot be avoided. Recently there has been a growing trend towards
the use of block sampling of granular soils for laboratory dynamic testing.

Block sampling has also been used in comparative studies to evaluate the quality of sampling for different sampling techniques.

The direct influence of block sampling and the resulting change of stress on the dynamic strength characteristics of sands has, however, not been investigated; particularly in view of the finding of Mori et al. (1978) that merely a removal of the confining pressure on previously strained samples can cause them to lose about 30 percent of the dynamic strength gained as a result of previous straining, it seems important to determine the effects of block sampling alone.

Accordingly the large diameter test facility used for tube sampling and described in Chapter 3 was utilized to create deposits of known dynamic characteristics. A system employing a combination of advance trimming and block sampling was designed to secure block samples from these deposits. Following a brief review of the past attempts to obtain and test block samples for cyclic load testing, the procedures used in this investigation will be described in this chapter. Techniques used for setting up and testing the block samples and a discussion of the test results will also be presented.

4.2 Review of Past Attempts to Block Sample for Cyclic Load Testing

There is only a very limited data available on the cyclic load testing of block samples. This is perhaps due to the fact that block sampling is an expensive and time-consuming procedure, particularly where the material in question is below the ground water table and dewatering is required. Nevertheless some investigators have recently used this procedure mainly to set up a basis to evaluate the quality of samples obtained by other sampling techniques.

Cyclic strength data reported by Horn (1978) on block samples have indicated substantially greater cyclic strength than that of fixed piston samples. Similar observations were reported by Espana et al. (1978) and by Marcuson and Franklin (1979). Salomone et al. (1978), however, found out that the cyclic strengths of block and tube (Pitcher and Denison) samples are not much different.

Except for the Salomone et al. test data, the above mentioned block sampling was carried out in dense material and therefore the effects of possible loosening of the soil during tube sampling cannot be ruled out. Horn attributed the considerable scatter in his data to the variation in gradation, density, cementation and possibly other factors which should be expected when dealing with undisturbed samples. Espana et al. explained that each sample, whether from tubes or blocks, exhibited physical differences due to the alluvial nature of the deposit involved, producing numerous small layers and lenses of sand and clay within individual test specimens; and hence the behavior during cyclic loading may have been affected by peculiarities within individual specimens. Data by Marcuson and Franklin were, however, obtained from a relatively uniform deposit. A test fill was prepared by compacting sand by a vibratory roller and samples were taken with a fixed piston sampler and with a block sampling technique utilizing a GEI sampler. The average dry density (105 pcf) of the block samples was higher than the dry density (102 pcf) of the piston samples and the cyclic strengths of the block samples were also substantially higher (Fig. 4-1).

In the case of variably cemented sands tested by Salomone et al., dry densities (75 to 114 pcf) of the Pitcher and Dension samples were higher than those of the block samples (73 to 93 pcf) indicating a

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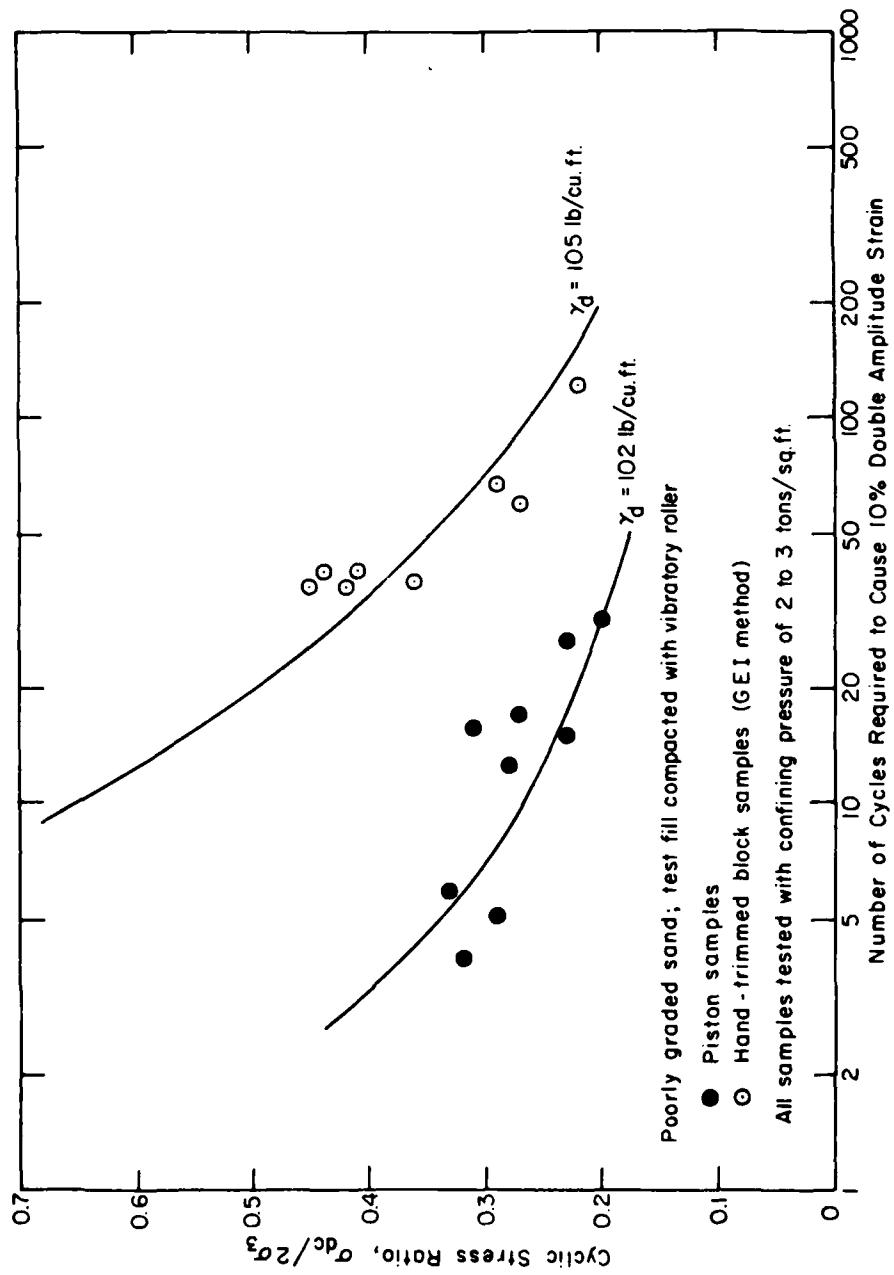
FIG. 4-1 COMPARISON OF CYCLIC LOADING CHARACTERISTICS FOR BLOCK SAMPLES AND
          TUBE SAMPLES

(After Marcuson and Franklin, 1979)

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densification by Pitcher and Denison samplers. Yet the cyclic strengths were similar. The stress-strain relationships from static tests, however, indicated that the block sampling technique provides samples which were substantially less disturbed than tube samples.

In view of the results discussed above, it can be concluded that block sampling provides samples which are substantially less disturbed and further that their cyclic strengths in the case of dense sands, are usually greater than those of tube samples. However complicating factors such as the variability of soil from specimen to specimen, opening of cracks or fissures, and change in in-situ state of stress due to de-watering and excavation make it difficult to assess the amount of disturbance suffered by the block sample itself; hence it does not provide a reliable basis for evaluating the disturbance resulting from other sampling techniques. Clearly there is a need to study the nature and degree of disturbance due to block sampling alone particularly in view of the fact that laboratory preparation techniques used in trimming a suitable test sample from a block sample can play a critical role in determining the representative cyclic strength for the natural deposits. Accordingly the 12 inch diameter sample testing facility at the University of California was used as described in Chapter 3 to create deposits of known dynamic strength characteristics. Block samples were then obtained from it employing the procedures described in the following pages.

4.3 Description of the Testing Equipment

(a) The Large Cyclic Triaxial Machine

The cyclic triaxial set up capable of testing 12 in. diameter samples has been described by Wong (1971). Major modifications made for

the purposes of undisturbed sampling have already been described in Chapter 3. The only difference is in the use of the cap. While the sampling cap was used for push tube sampling described in Chapter 3, a conventional cap was used for this investigation.

(b) The Block-Sampler

When compared to the tube samples, block samples have the disadvantage of requiring a significantly large amount of trimming as well as the possibility of disturbance of the material in cutting laboratory test specimens. In order to overcome some of these difficulties, particularly those related to the disturbance associated with the trimming for a laboratory size specimen, a special block-sampler was designed. The block sampler was essentially a split mold (Fig. 4-2) with an inside diameter equal to the diameter of the test specimen. A cutting shoe was slipped on one end of the sampler. No inside clearance was provided at the cutting edge and the friction between the sample and inside of the sampler, which was a stretched membrane as will be explained later under the block sampling procedure, was minimized by coating the membrane walls with vaseline.

4.4 The Description of the Sand and the Method of Sample Preparation

Monterey #0 sand was used in this study and was obtained from the same stock-pile as for the study of push tube sampling described in Chapter 3. Important characteristics of this sand have already been presented in that chapter.

A specially designed pluviation method was used to prepare homogeneous samples 12 inches in diameter and 27 inches in height. A detailed description of the method has been presented in Chapter 3.

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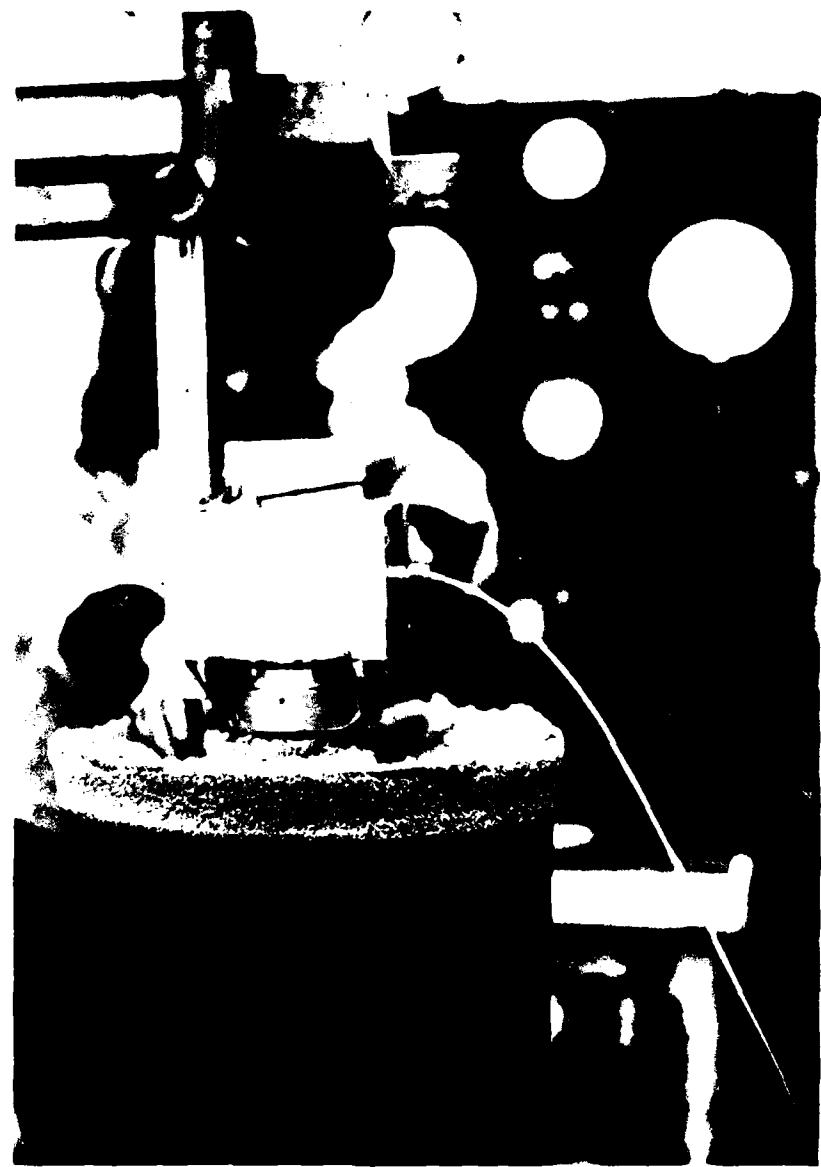
FIG. 4-2 SET-UP FOR BLOCK SAMPLING

4.5 The Testing Program and the Test Procedures

Four different series of testing were involved in studying the effect of block-sampling on the seismic history characteristics of Monterey #0 sand. The first three series of tests were made on 12 inch diameter specimens, and the fourth series involved testing of 2.8 inch diameter samples obtained by the block-sampling technique.

The objective of each of the test series was as follows:

1. Test Series 4-A was performed to establish the cyclic strenqth characteristics of a freshly deposited sand at a relative density of 60 percent.

2. Test Series 4-B was performed to establish the cyclic strenqth characteristics of sand samples which in addition to their being freshly deposited at 60 percent relative density had been given a known seismic history effect following the procedures used by Seed et al. (1975).

3. Test Series 4-C was performed to obtain 2.8 inch diameter test samples by block sampling from the 12 inch diameter specimens which had previously been given the same seismic history effects as were the specimens from test series 4-B.

4. Test Series 4-D was performed to set up and test 2.8 inch diameter samples obtained by block samplinq under test series 4-C.

The procedures for test series A and B which set up the basic relationships have already been described in Chapter 3. The lines on a typical stress ratio versus number of cycles plot describing these relationships had been referred to as virgin and seismic history lines respectively (Fig. 3-8). These relationships provide the basis to evaluate the effects of disturbance due to block samplinq.

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Test procedures for series 4-C and 4-D are briefly described below.

Test Series 4-C

Following identical procedures for sample preparation as for series A and B, the sand was poured in the 12 inch diameter mold to a relative density of 60 percent. After the surface of the specimen was levelled by cutting and scooping off excess sand, a conventional cap was set on the top of the sand and vacuum was applied both from the top and bottom of the specimen to help remove the mold. The specimen was then sealed by tightening membrane clips. Subsequent steps from the setting up of the triaxial chamber, application of confining pressure, saturation and finally the application of the seismic history effects were similar to those used for test series B and described in Chapter 3.

After the seismic history effects had been applied the specimen was put under vacuum by gradually lowering the chamber and back pressures. The triaxial chamber was then disassembled to allow access to the specimen which was now ready for block sampling.

4.6 The Block-Sampling Procedure

A combination of advance trimming and block sampling, by gently pushing the block sampler over the trimmed column, was employed. Sampling by this method is quite slow and requires a very careful and rigid set up so that no rocking or lateral movement of the block sampler takes place while it is held vertically and advanced over the trimmed column. Accordingly the block sampler was attached to a rigid metal rod which in turn was held in position with the help of a rectangular plate clamped on the tongs of a fork lift, this in turn was rigidly supported by props.

A system of screws was used to advance or to hold the rod and the block sampler in position (Fig. 4-2). After aligning the block sampler vertically over the specimen, the cap of the 12 inch diameter specimen was removed and the membrane carefully folded down to expose the surface of the specimen. The application of the vacuum had partially drained the specimen and the exposed top few inches of the specimen retained its shape due to the apparent cohesion provided by the capillarity.

The actual sampling procedure began by pushing the sampler a short distance (about 1 cm) into the soil. The soil around the sampling tube was carefully removed by a spoon and other suitable hand tools. The trimming was continued for a distance of about 1/2 to 1 inch ahead of the cutting edge to a diameter slightly larger than that of the sampling tube. The sampler was then lowered and the cutting edge shaved off the excess soil. This procedure of alternatively trimming and advancing the sampler was continued until the desired length of the sample, which in this case was equal to the length of sampling tube (about 6.5 in.) was obtained and the soil sample was protruding about 1 inch above the sampler. Finally the sample was severed from the 12 inch diameter specimen by carefully inserting a thin stainless steel plate under the cutting edge. The block sampler was then freed from the connecting rod and gently hand carried to the 2.8 inch diameter sample testing device.

Test Series 4-D

In this test series, 2.8 inch diameter block samples were cyclically loaded to determine their dynamic strength characteristics. The major part of the effort was involved in retrieving the sample from the block sampler and in setting it up for the final testing.

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First the protruding portion of the sample was trimmed flush with the top of the sampler. It may be recalled that the block sampler was made like a split mold such that a membrane was mounted and stretched flush against its walls with the help of a vacuum which remained applied during the sampling operation. The triaxial cap was set on the trimmed top of the sample and vacuum applied through the top drainage line. The membrane was released from the block sampler top onto the triaxial cap thus helping the vacuum become more effective. The sample meanwhile was still held securely within the block sampler mold.

The next difficult step was to remove the cutting shoe without unevenly breaking the soil from the bottom of the sampler. Because of the vacuum acting through the top drainage line, the sampler could be placed on its side or in an upside-down position. A plug slightly smaller than the inside diameter of the cutting shoe was used to keep the soil slightly pushed towards the top of the sample while the cutting shoe was gently pulled out leaving the soil protruding out from the edge of the sampler mold. It was now easy to trim the protruding soil flush with the bottom of the sampler-mold.

Two alternate but equally effective procedures were then used to set the sample on the base of the triaxial machine. In one of the procedures, the entire sampler-mold along with the triaxial cap was carefully set on the base of the triaxial machine. As the method of sampling by advance trimming involves removing instead of pushing aside of the soil, the wall thickness of the sampler is only of minor importance. Accordingly, the sampler was purposely designed with thick walls to minimize vibrations and thus to provide greater stability. Therefore in order to avoid the

relative movement of the mold with respect to the soil sample as the mold was being dismantled, suitable props were placed under the thick walls of the mold. This proved to be very successful and the mold was split open and easily removed after the membrane was released on to the triaxial base and the O-ring seals were put in place. The sample was now ready to receive the chamber.

In the case of the second procedure, a detachable base with a built-in valve to open and close the bottom drainage line as desired was used. The principle was essentially the same as that used for the push tube sample set-up. The sampler-mold was laid flat on the table and the triaxial base with its valve open and vacuum acting through it was set against the bottom face of the sample. The membrane was then released from the mold on to the base. The sample was now under an effective vacuum. The sampler-mold was then split open and the soil sample was carried in a vertical position to the triaxial frame. Next, the base was securely bolted to the bottom of the triaxial cell and the sample was now ready to receive the chamber.

The sample was then saturated following the conventional procedures described in Chapter 3, under an effective confining pressure corresponding to that used for the large diameter specimens. Finally the sample was cyclically loaded to 100 percent pore pressure ratio and significant strains. The test results are shown in Fig. 4-3. The strengths of the block samples were intermediate between those of the virgin and "strain history" samples indicating a partial loss of the resistance gained due to previous seismic history effects. Clearly the block sampling, handling and testing procedures had caused some disturbance. Although the average

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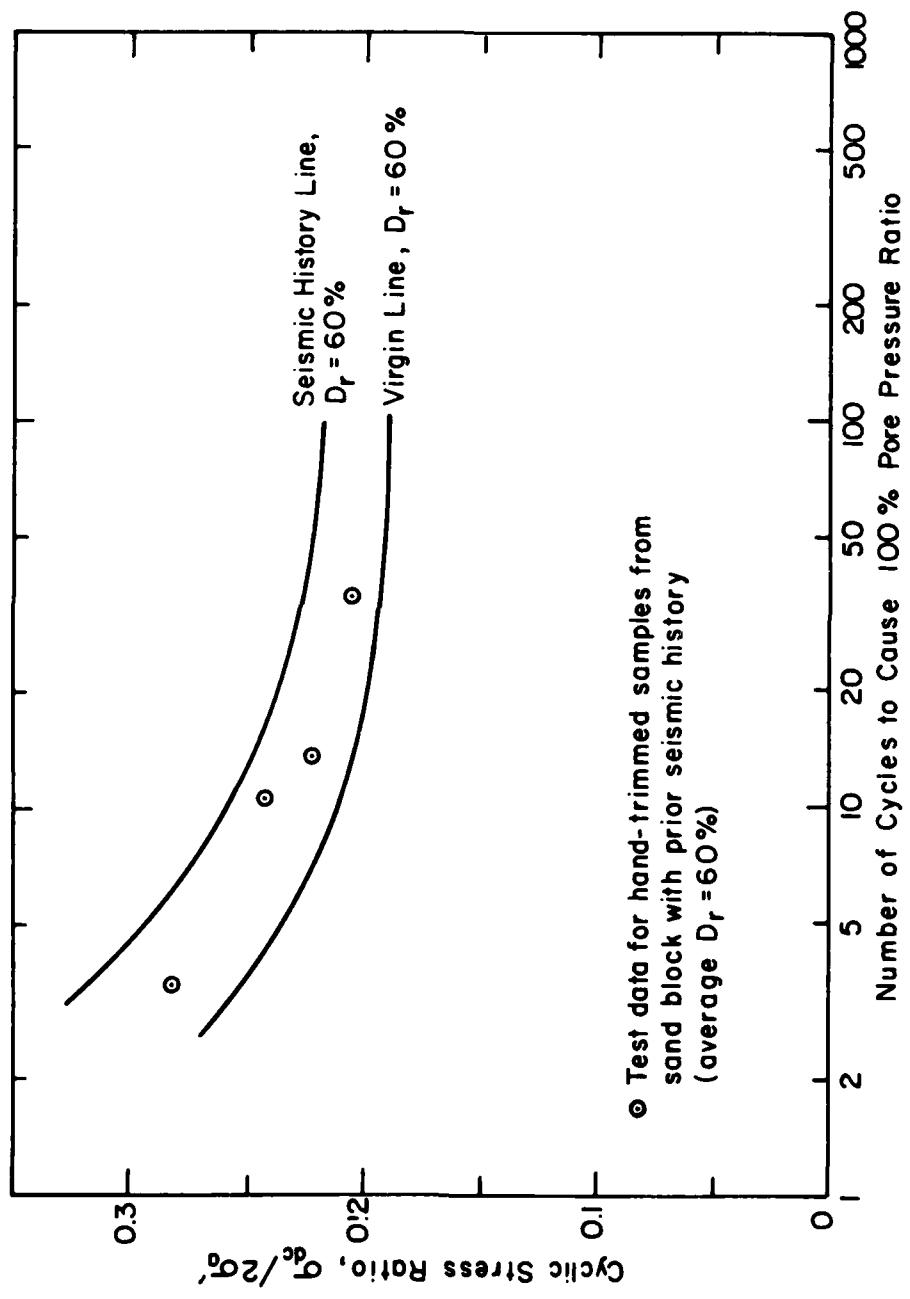
FIG. 4-3 EFFECT OF BLOCK SAMPLING ON CYCLIC LOADING CHARACTERISTICS OF SAND
WITH PRIOR SEISMIC HISTORY

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density of the block samples compared very well with the density of the large specimen from which they were trimmed, and in spite of the great care used in preparing the test specimens, the sampling, handling and testing combined to cause undesirable grain movements and some loss of strength. Soils with fines may provide better particle adhesion and for such soils block sampling may provide a very high quality sample not obtained by any other conventional method currently available.

4.7 Discussion

Many factors can contribute to the disturbance due to sampling, and while block sampling provides an effective means of eliminating some of them, the disturbance due to the change in the state of stress as a result of excavation and dewatering cannot be avoided. As pointed out by Marcuson and Franklin (1979) changes in state of stress may produce significant changes in void ratio or density. Differences in the density values determined by block sampling and in-situ methods have been reported (Horn, 1978).

Relieving of residual stresses may cause slight expansion of the soil and hence the dry unit weights of block samples are likely to be less than the in-situ unit weights. Little is known however concerning the quantitative evaluation of the change in the state of stress and associated change in density due to excavation and dewatering. It is likely that changes in density due to sampling would increase as the change in the stress (or overburden pressure) increases. In addition to the difficulty in evaluating the disturbance due to stress change, the amount of disturbance solely caused by the laboratory preparation procedure could not be determined. Some disturbance might also have occurred during

actual sampling by advance trimming. The combined effect of all of these disturbances was, however, to cause no significant change in density and the cyclic strength due to seismic history effects was not completely lost either. For soils with a higher content of fines, the nature of grain contacts is likely to be influenced to a lesser extent by these disturbances and block sampling might still be the best available method for obtaining undisturbed samples of these soils.

Most block sampling experience to date has been with cohesive soils and the laboratory preparation techniques have not involved great difficulties. With sands, careful handling and often special techniques are required to obtain specimens suitable for laboratory cyclic strength testing from block samples. Hand trimming or freezing the partially drained block samples by the application of dry ice or liquid nitrogen and then coring suitable samples are some of the techniques used for laboratory preparations. Comparative studies on specimens obtained by hand trimming and freezing methods for laboratory preparation and handling would seem to be worthwhile.

CHAPTER 5

UNDISTURBED SAMPLING OF SANDS BY FREEZING AND CORING

5.1 Introduction

In view of the test results obtained from the push tube and block

sampling techniques and the difficulties in correctly assessing the

degree of disturbance caused by these techniques, it became apparent that

special procedures such as freezing prior to sampling and handling should

be investigated in the hope that this would maintain the in-situ structure.

Accordingly efforts were directed towards the development of a suitable

freezing method for securing truly undisturbed samples of sand. The

studies were aimed at freezing the ground first and then coring suitable

samples from it.

In the first phase of the studies, both theoretical and experimental

investigations were carried out to find means to eliminate or minimize

volume changes due to freezing.

Once an effective method to control volume changes was developed,

it remained, however, to determine whether this method involving freezing

and thawing would affect the liquefaction or cyclic strength characteris-

tics of the soil. Accordingly a second phase of the study was undertaken

to investigate the effect of a freeze-thaw cycle on cyclic strength

characteristics.

Finally in order to investigate the adaptability of this method to

in-situ freezing and sampling by coring, the third phase of the study con-

sisted of freezing a 12 inch diameter sample and coring a 2.8 inch sample

from it. A brief review of past attempts to freeze and sample, the testing

programs, the results of the tests and a discussion for each of the three phases of the studies are presented in this chapter.

5.2 Review of Past Attempts to Freeze and Thaw

For over a century, ground freezing has been used for soil stabilization and control of ground water. The first reported use of artificial ground freezing was in England in 1862 where freezing was used to stabilize soil for a marine shaft (Jones and Brown, 1977). The first attempts to obtain samples of undisturbed soil by freezing were made by the Corps of Engineers in sampling operations at Fort Peck Dam (Corps of Engineers, U. S. Army, 1938 and 1939). The procedure has been described by Hvorslev (1949). Complete freezing of the soil below the bottom of the bore hole was used and the sample was obtained by coring. Freezing was accomplished by circulating a freezing mixture through seven pipes driven in a circle around the bore hole, and samples of frozen ground 36 inches in diameter were obtained by coring. The quality of the samples was described as excellent on the basis of visual inspection and photographs of the frozen samples which had been sawed lengthwise into two parts (Hvorslev, 1949). Formation of ice lenses was observed in samples of shale and clayey materials but not in samples of clean sands and gravels.

Freezing of the bottom of the sample to prevent loss of a saturated sand sample during withdrawal was attempted also by the Corps of Engineers (Fahlquist, 1941a, 1941b, and 1942). The method consisted in advancing the casing to the cutting edge of the sampler and removing the soil between the sampler and casing by jetting utilizing an annular auger. An annular freezing unit was then lowered to the bottom of the hole and the lower part of the sample was frozen by circulating alcohol cooled with dry ice through the freezing unit.

Langer (1939) in France and Kollbrunner and Langer (1939) in Germany used freezing techniques for partial solidification of loose and very uniform fine sand and silt before sampling; freezing was accomplished by pumping a mixture of alcohol and dry ice through a series of pipes driven into the ground and advanced a little ahead of the boring.

Hvorslev, who was associated with the freezing studies conducted by the Corps of Engineers, noted (1949) that solidification before sampling is in some cases simpler than solidification of the lower part of the sample and may be required when drive sampling or core boring causes excess disturbance. Hvorslev further noted that this method of sampling is expensive but it is the only currently available method by means of which relatively undisturbed samples of coarse (sands) and gravelly soils can be obtained.

Thus it has long been recognized that sampling of saturated sands below the ground water table by freezing is an effective and reliable means to obtain undisturbed samples; yet, because of its high cost, this method has been used only rarely. Instead samples of cohesionless soils were often remolded before testing and it was felt that by placing the soil to the in-place density, in-situ soil strength would be adequately modeled in the laboratory. Recently, however, research has shown that samples of the same density can have widely different cyclic strengths, a phenomenon attributed to differences in grain structure, strain history, and sustained loading. The method of freezing appears to provide a potential means to preserve the in-situ structure produced by the various

most recent attempts to obtain undisturbed samples of sand by been reported at the 9th International Conference on Soil

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lower part of the sample was frozen by circulating alcohol cooled with dry

ice through the freezing unit.

Mechanics and Foundation Engineering by Yoshimi et al. (1977). By circulating a mixture of ethanol and crushed dry ice through an open thin wall steel tube, 73 mm in diameter, and inserted vertically into the ground, Yoshimi et al. were successful in freezing a column of sand having a constant diameter. The steel tube together with the frozen column of sand was pulled out and sawed into suitable pieces for testing. The quality of the samples so obtained was evaluated in terms of the change in density. In addition, full-scale radial freezing tests were carried out in the laboratory to evaluate the change in density. One dimensional freezing tests were also conducted to study the effect of surcharge on vertical strains due to freezing (Fig. 5-1). In a companion paper Yoshimi et al. (1978) presented additional data on the effect of density and percent fines on the vertical strains during freezing and on the effect of freezing and thawing on the static strength and deformation characteristics (Fig. 5-2). Negligible effects were observed. On the basis of these studies, Yoshimi et al. concluded that high quality undisturbed samples of sands can be obtained by using the proposed radial freezing method.

Whereas the studies by Yoshimi et al. provide valuable data on the fundamental aspects of the effects of freezing, including the effect on static strength characteristics, the problem of the effect of the proposed radial freezing method on the dynamic strength characteristics has yet to be resolved.

Ishihara and Silver (1977) and Silver and Ishihara (1978) used a quick-freezing technique with liquid nitrogen sprayed on the tube to stabilize samples of sand while they were being transported from field to laboratory. The samples were obtained from the ground in their natural state

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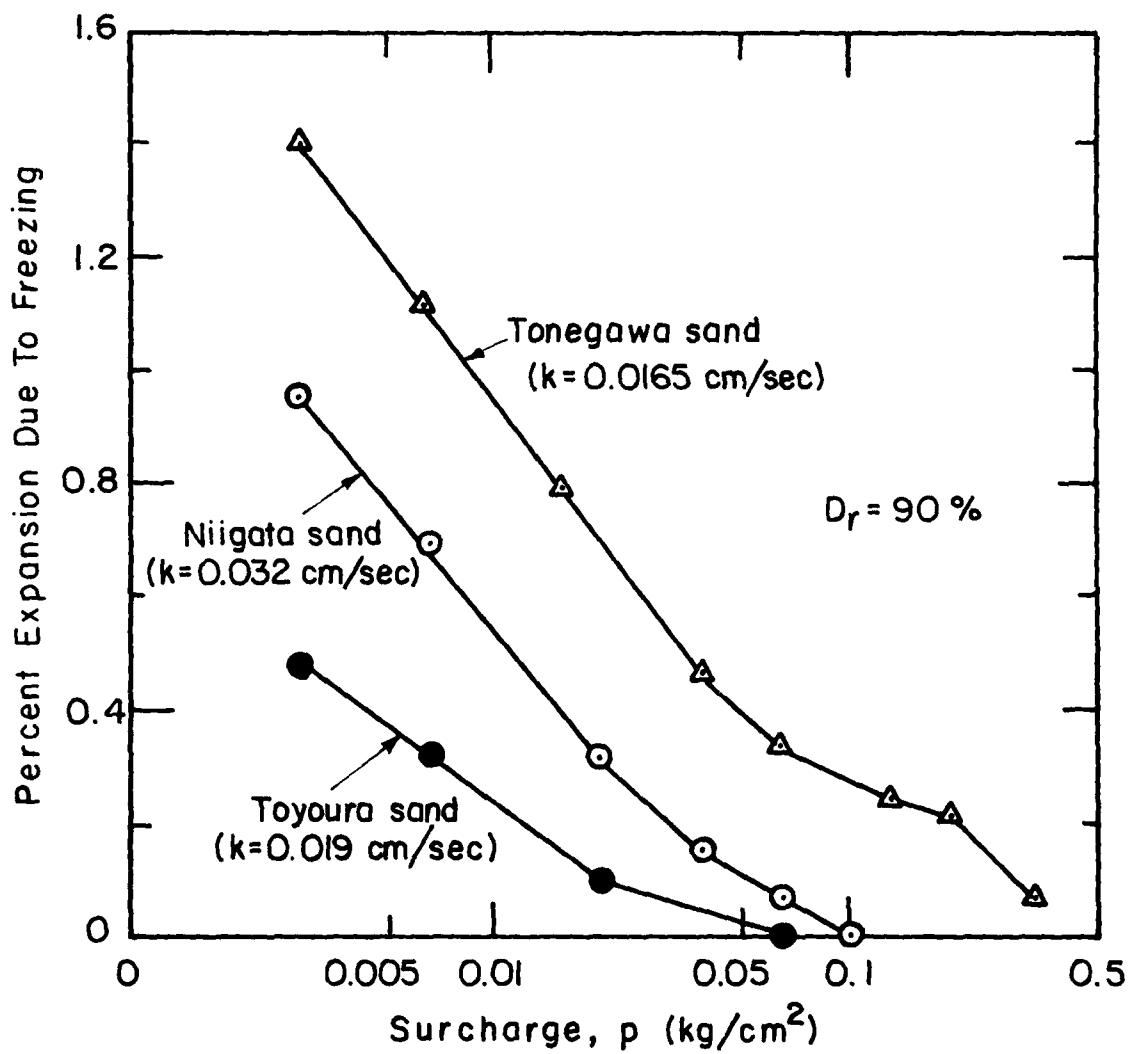
FIG. 5-1   EFFECT OF SURCHARGE ON EXPANSIVE STRAINS DUE TO
FREEZING

(After Yoshimi et al., 1978)
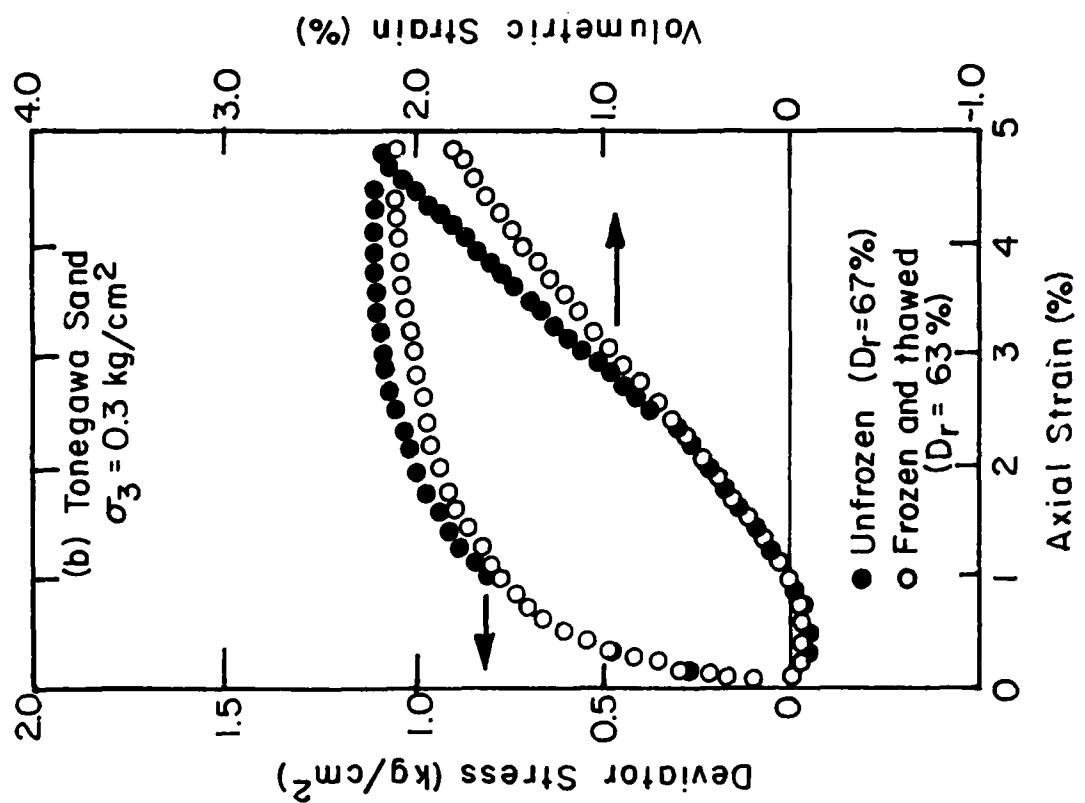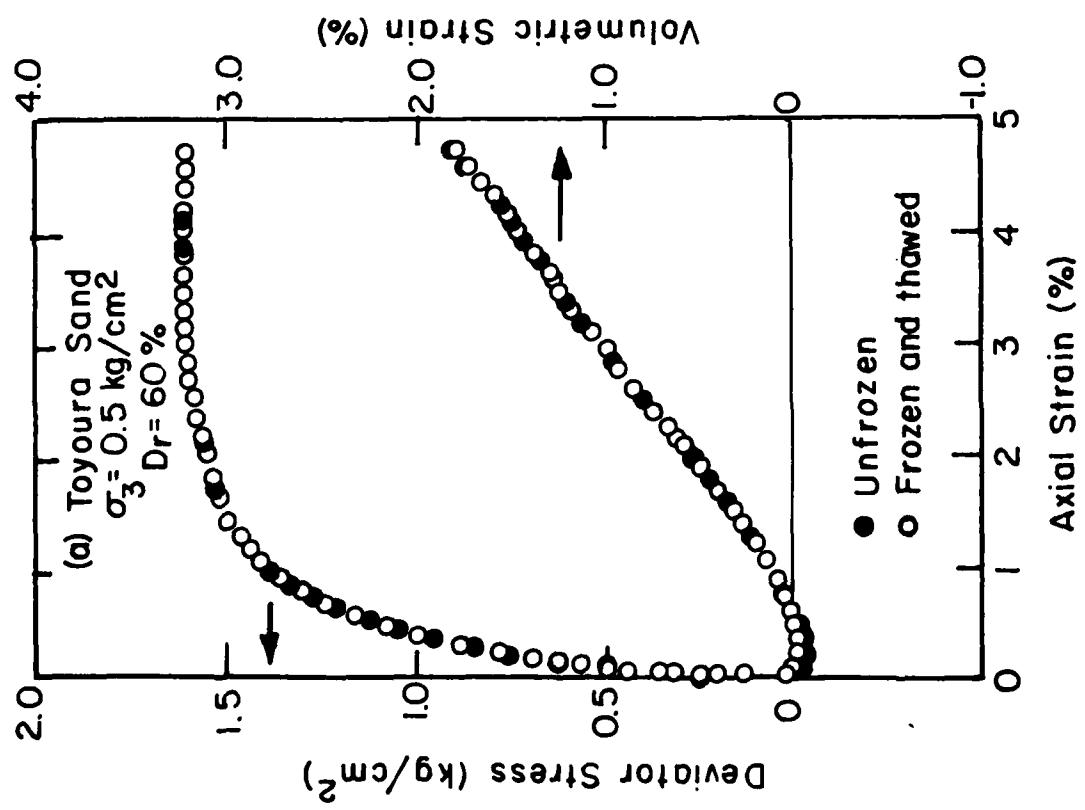
FIG. 5-2 EFFECT OF A FREEZE-THAW SEQUENCE ON STRESS-STRAIN AND DILATANCY CHARACTERISTICS
(After Yoshimi et al., 1978)

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and were first allowed to drain freely for periods of 12 to 24 hours, depending upon the amount of fines, and then frozen. The quality of the frozen specimens was checked by noting the specimen volume both before and after freezing and no measurable differences were reported. This was because drainage was used to clear the soil voids of excess water. It may be noted that since the studies by Ishihara and Silver and by Silver et al. were aimed mainly at studying the effect of large diameter sand samples on the undisturbed and remolded cyclic strengths of Niigata sand, no specific data was reported on the effect of freezing on the cyclic strength characteristics.

Walberg (1978) is perhaps the only investigator to present data on the effect of freezing on cyclic strength characteristics. Walberg studied the effect of freezing on cyclic triaxial behavior of undisturbed and reconstituted samples. The samples had been drained or partially drained before freezing which was accomplished by surrounding the specimen with dry ice. No significant effect on the density or cyclic strength was reported. Samples, however, had been given no known dynamic characteristics prior to freezing in order to provide a bsis for evaluating the degree of disturbance.

5.3 Mechanics of Artificial Freezing of Soils

The basic concept in freezing of soils is the removal of heat from the ground, causing the pore water to freeze and to act as a bonding agent. In order to provide a physical basis for the understanding of the phenomenon of freezing and thawing of soils, a brief review of frozen soil mechanics is presented in this section. Selection of the freezing method used in this investigation was based on the knowledge of the physico-chemical aspects of these phenomena.

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While classical soil mechanics deals with the mechanics of a two or three phase system, frozen soil mechanics deals with an even more complex system of particles that is at least a four phase system containing: (i) solid mineral particles, (ii) ideally plastic ice inclusions (connecting ice and interlayer ice), (iii) water in the bonded and liquid state and (iv) gaseous components. A complete discussion of this subject is beyond the scope of this dissertation. In this section the presentation will be limited to a brief description of the physical and some of the chemical aspects of the processes that take place during freezing. An excellent treatment of the subject of physico-chemical and physico-mechanical phenomena accompanying the freezing of soils is given in Professor Tystovich's book, Principles of the Mechanics of Frozen Soils, (Academy of Sciences, U.S.S.R., 1952).

Although the part played by each of the constituents listed above has some bearing on the overall behavior of frozen soils, research done over recent decades by Soviet authors (Symgin, 1929, 1937; Tsytovich, 1953, 1955, 1968, 1975; Gol'dshteyn, 1940, 1948; Puzakov, 1964; Nersesova, 1967 and many others)* and by other scientists (Taber, 1930, Penner, 1973, and Jumikis, 1974 and others)* has shown that the basic process in freezing soils is a redistribution of moisture as a result of migration of water during freezing and deposition of ice. Therefore the problem of moisture migration in freezing soils is considered to be of great importance and has a direct bearing on the development of any artificial freezing method for obtaining undisturbed samples, particularly in view of the reported observations that the freezing may create conditions such that an increase in soil volume occurs due to migration of moisture towards the freezing

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*Summarized in English in Tsytovich's book entitled The Mechanics of Frozen Ground.

front (Tsytovich, 1975). A thorough understanding of the physics of moisture migration is required before attempting to minimize or eliminate volume changes due to freezing.

A number of theories has been advanced to explain the migration of moisture during freezing, mostly based on the premise that migration forces cause motion of pore water in freezing soils only when phase equilibrium is disturbed and conditions are created for the appearance of various gradients; namely, moisture, temperature, adsorption film, osmotic pressure, capillary and isoboric potential of mineral particle free energy. However no integrated theory of moisture migration has yet been elaborated in general form; and reliance must, therefore, be placed on the results of direct measurements of moisture migration.

Russian agronomists were perhaps the first to systematically study the distribution of moisture in freezing soils around the end of the nineteenth century and the first experimental data on the redistribution of moisture was reported by Bliznin (1887, 1889). Subsequently although several authors have reported field observations on moisture migration, it was the controlled experiments of Sumgin (1929) and Taber (1930) which helped to define the process of moisture migration more clearly.

Taber observed considerable migration of water towards the cooling surface in his experiments in which cylindrical specimens of clay were frozen. Apparently the freezing source was applied at the top of the specimen, and after freezing, thick interlayers of ice were formed at the tops of the specimens while the moisture contents at the bottom were reduced by an average of 16 to 25 percent. Many more investigators in the U.S.S.R., U.S.A. and other cold countries continued to study moisture migration and at this time a large amount of factual information

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characterizing the influence of particle size, mineralogical composition, exchange bases and capillary phenomena on the migration of water in freezing soils has been accumulated. Among these, the studies by Bozhenova and Bakulin (1957) have most direct relevance to this investigation.

Bozhenova (1940) and Bozhenova and Bakulin (1957) observed different water migration effects in clays and sands: the moisture contents of clays increased in the direction towards the freezing front, whereas the moisture content of medium grained sand decreased. Clearly this last fact is of considerable importance for practical purposes in order to be able to determine how water migrates when sandy soils are artificially frozen and to study the conditions under which this effect occurs without causing any volume changes. Fortunately one such study has been reported by Tsytovich (1955). He had made a detailed study of this problem and concluded: "It was established that in water saturated sands with free drainage of water in at least <u>one direction</u>, water does not migrate towards the freezing point, but is squeezed out, with the result that the porosity of frozen water-saturated sands remains practically the same," (Tsytovich, 1975). It was also confirmed by Tsytovich that in fully water saturated particulate soils, water migrates in the liquid phase.

Tsytovich's experiments provided another significant insight into the influence of the external (or confining) pressure on the unfrozen water contents and consequently on the volume change tendencies of freezing soils under confining pressures. The results of Tsytovich's experiments for clayey soils indicate that external pressure strongly increases the unfrozen water contents in frozen soils and that this effect

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is larger the higher the pressure under which the soil is frozen, indi-
cating therefore that the phase change and hence the expansion tendencies
can be minimized if freezing is accomplished under confining pressures.
Recent studies by Yoshimi and Hatanaka (1977), Jones et al. (1977) and
by Yoshimi et al. (1978) provide valuable data on the influence of sur-
charge (or confining pressure) on the volume change tendencies of sands.
Test data by Yoshimi et al. indicate no measurable expansion for a typical
alluvial sand from Niigata when the surcharge reached about 0.1 kg/cm^2
which is equivalent to an overburden pressure in the field at a depth of
about 1.0 m or less. Higher surcharge was required as the percentage of
fines increases.

Clearly the best way to freeze sands in order to maintain their
in-situ conditions seems to be by unidirectional freezing (i.e., not
impeding the drainage) with the confining pressure maintained. Accordingly
efforts were directed towards the development of laboratory testing equip-
ment where specimens could be frozen unidirectionally.

5.4 Development of a Freezing Method

Since triaxial equipment provides a convenient control on the con-
fining pressure and studies of both axial and lateral expansion can be
made, a conventional triaxial equipment was chosen for the freezing
experiments and modified for freezing triaxial specimens from bottom to
top. The base was to act as a cooling source and was made of brass with
a groove in it for circulation of the coolant. The coolant used was
ethanol whose temperature was lowered and regulated by adding dry ice
intermittently. The coolant was circulated with the help of a pump capable
of handling fluids at temperatures as low as -80°F. Monterey #0 sand was

used for sample preparation. The description of the sand is the same as that described in Chapter 3 except that it has been obtained from a different stock pile and its minimum and maximum densities were respectively 89.5 pcf and 105.3 pcf. A specimen 2.8 inches in diameter was prepared using the tamping procedure used by Mulilis et al. (1975).

The first few attempts to freeze specimens brought into focus various important considerations in the development of the freezing method. Problems associated with radiation and poor conduction, as the sample freezes, seemed to adversely affect the efficiency of the system. From the observation of an extremely slow advance of the freeze front (1/8" in 5 hours) and from the increasing amount of frosting on the base of the cell, on the pump and on the tubings carrying the coolant, it became apparent that the lower conductivity and increased length of path resulting from the frozen portion of the specimen was making it increasingly difficult to remove energy from it; thus, after a while, the freezing system removed heat energy only from the base of the triaxial cell and not from the soil specimen. These observations, when interpreted in the light of available literature on the conductivity of frozen soil, indicated a need for a larger capacity and higher efficiency freezing system. Accordingly the circulation of small quantities of coolant through the base cap was abandoned and the entire bottom of the triaxial cell was dipped into coolant contained in a specially designed foam container to reduce radiation problems. The temperature of the coolant was lowered to a minimum of -80°F. This method proved to be extremely effective. As freezing progressed from the bottom up, water was seen flowing out through the top drainage line which passes through the top of the triaxial

cell, slightly modified for the purpose, and then to the back pressure line via the volume change device. The volume change device allowed measurements of the direction and amount of water flowing from the specimen. These trial specimens were completely saturated and had been consolidated under an effective confining pressure of 0.56 kg/cm^2 (cell pressure of 2.06 kg/cm^2 and back pressure equal to 1.5 kg/cm^2). Thus the water was flowing out against a back pressure of 1.5 kg/cm^2. Average freezing time for these specimens was on the order of 10 hours.

5.5 Effect of the Freezing Method on Volume Changes

Once the freezing system was developed, the first series of tests were made to examine the volume changes, if any, resulting from freezing. As a specimen became completely frozen, as evidenced by the appearance of frosting on the outside of the specimen and from no pore pressure response resulting from cell pressure increase, the cell pressure was taken off and the triaxial chamber disassembled to allow access to the frozen specimen. Diameter and height readings were taken on the sample and no changes were observed. While the specimen was still frozen, in a quick succession the chamber was reassembled and the cell pressure restored. The specimen was then allowed to thaw in a direction opposite to that of the freezing process. Since the top drainage line had remained connected all along to the volume change device, water could flow into the sample as thawing progressed. It was significant to note that the amount of water expelled was approximately equal to the theoretical volume change which would be expected as a result of phase change from water to ice. Furthermore an approximately equal amount of water was drawn in upon thawing. A complete record of the rate of water flow was kept during both

the freeze and thaw cycles. Figure 5-3 shows typical flow rate curves for two of the tests. It may be noted that the flow rate reaches a peak value as the maximum temperature gradients are reached and the phase change sets in.

On the basis of the tests and observations reported above, it was concluded that the method of unidirectional freezing (under confining pressure) causes no volume changes in the sands tested. But, whether this method, involving a freeze-thaw cycle, affects the liquefaction characteristics or not, remained to be verified. Accordingly, the next series of tests was undertaken to study the effect of the freeze-thaw cycle on the changes in cyclic loading characteristics resulting from a prior seismic history.

5.6 Cyclic Load Testing of Freeze-Thaw Samples

Since the lack of any significant change in density does not necessarily ensure the preservation of the cyclic loading characteristics acquired as a result of a past history of shaking or seismic loading, it was considered important to investigate the effect of the proposed freezing method on the dynamic soil characteristics. The effect of previous strain history on the subsequent behavior of a sand under cyclic loading conditions is a relatively well studied effect and it is very sensitive to the effect of disturbance. Accordingly the next series of tests involved preparation of samples with a known seismic (strain) history and then subjecting them to the freeze-thaw cycle before final loading to the 100 percent pore pressure ratio and significant strains to observe whether the freeze-thaw cycle had affected their behavior.
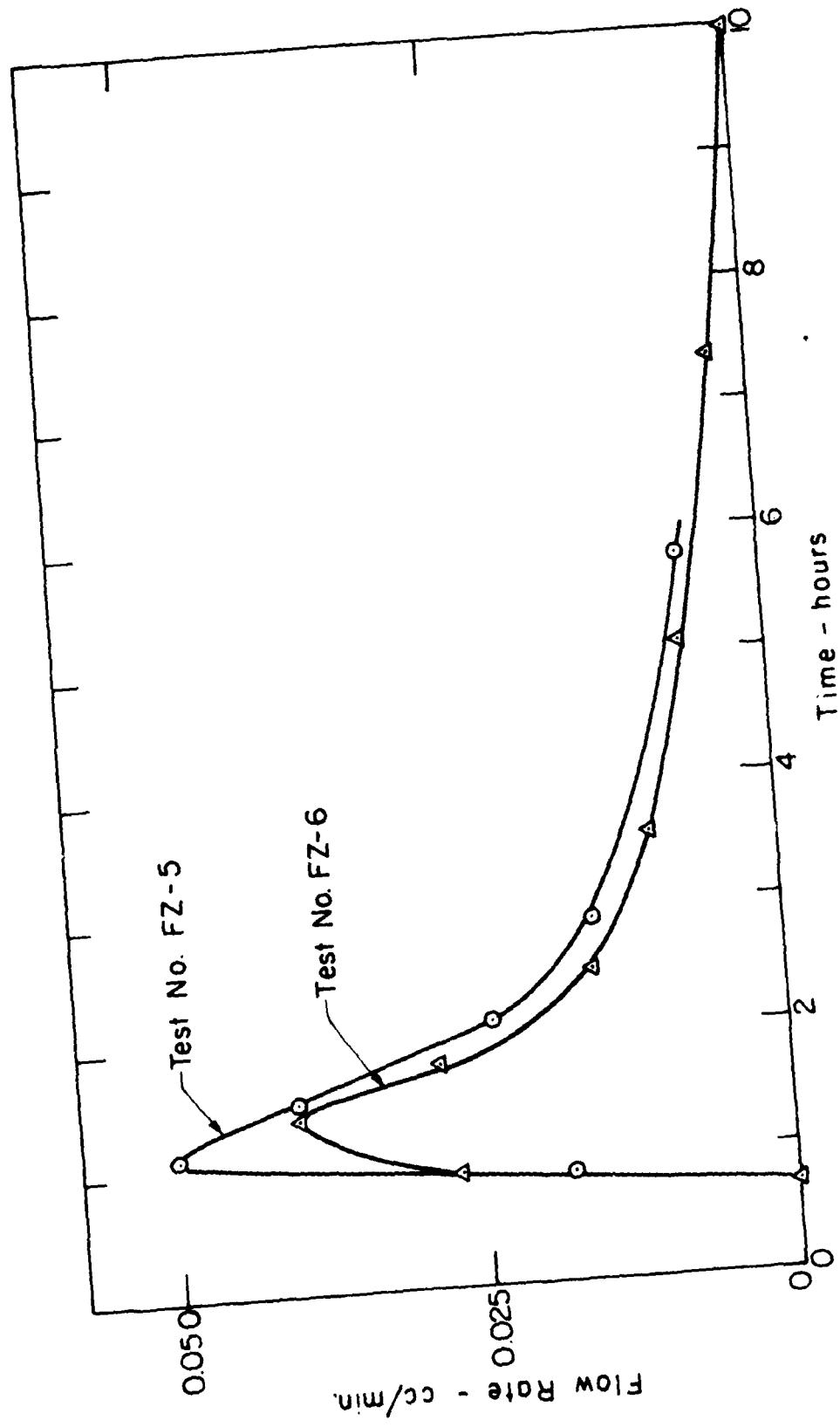
FIG. 5-3 TYPICAL FLOW-RATE CURVES

MICROCOPY RESOLUTION TEST CHART
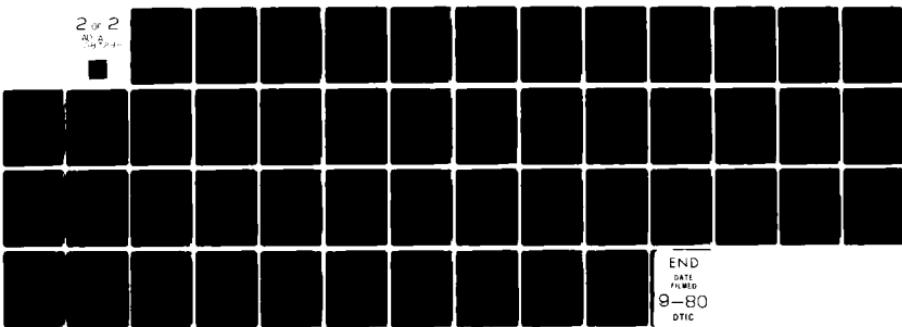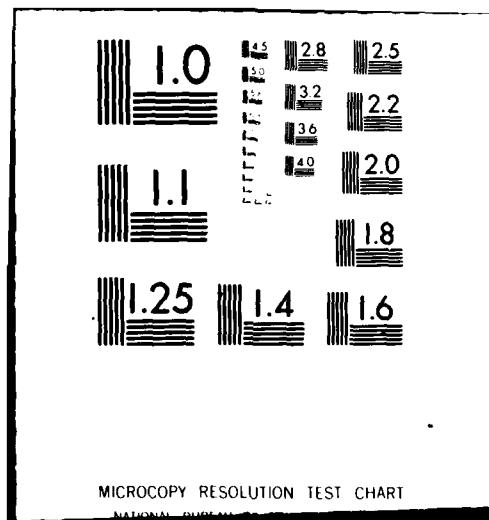
Base line characteristics were first established by testing tamped specimens prepared following procedures described by Mulilis et al. (1975). All the specimens were prepared identically to a relative density of about 48 percent; they were then saturated and consolidated under a cell pressure of 2.06 kg/cm^2 and a back pressure of 1.5 kg/cm^2. One set of these specimens was then subjected to cyclic triaxial tests until a pore pressure ratio of 100 percent was reached. A virgin line (i.e., with no prior strain history effects) was thus established. Another set of these specimens was first subjected to a known seismic history using procedures described by Seed, Mori and Chan (1976) and then cyclically loaded to the 100 percent pore pressure ratio condition. Thus a cyclic loading characteristic curve influenced by seismic history was established. This set of curves (Fig. 5-4) was used as a basis for comparing the results of specimens subjected, in addition, to free-thaw cycles.

Another identical sample was therefore prepared and given the same seismic history. The specimen was then frozen utilizing the unidirectional freezing method described above. Upon completion of freezing and thawing, which took about 20 hours, the specimen was cyclically loaded to a cyclic pore pressure ratio of 100 percent. Test results for this specimen are shown in Fig. 5-5. The specimen showed no loss of the increased resistance acquired by virtue of the seismic history to which it had previously been subjected. It may be noted that the test results compared remarkably well with those of the baseline specimens (not subjected to the freeze-thaw cycle). Similar results were obtained in tests on two other specimens (see Fig. 5-5).

After complete freezing of the samples described in the preceding paragraph, thawing was permitted to take place soon after; and the confining
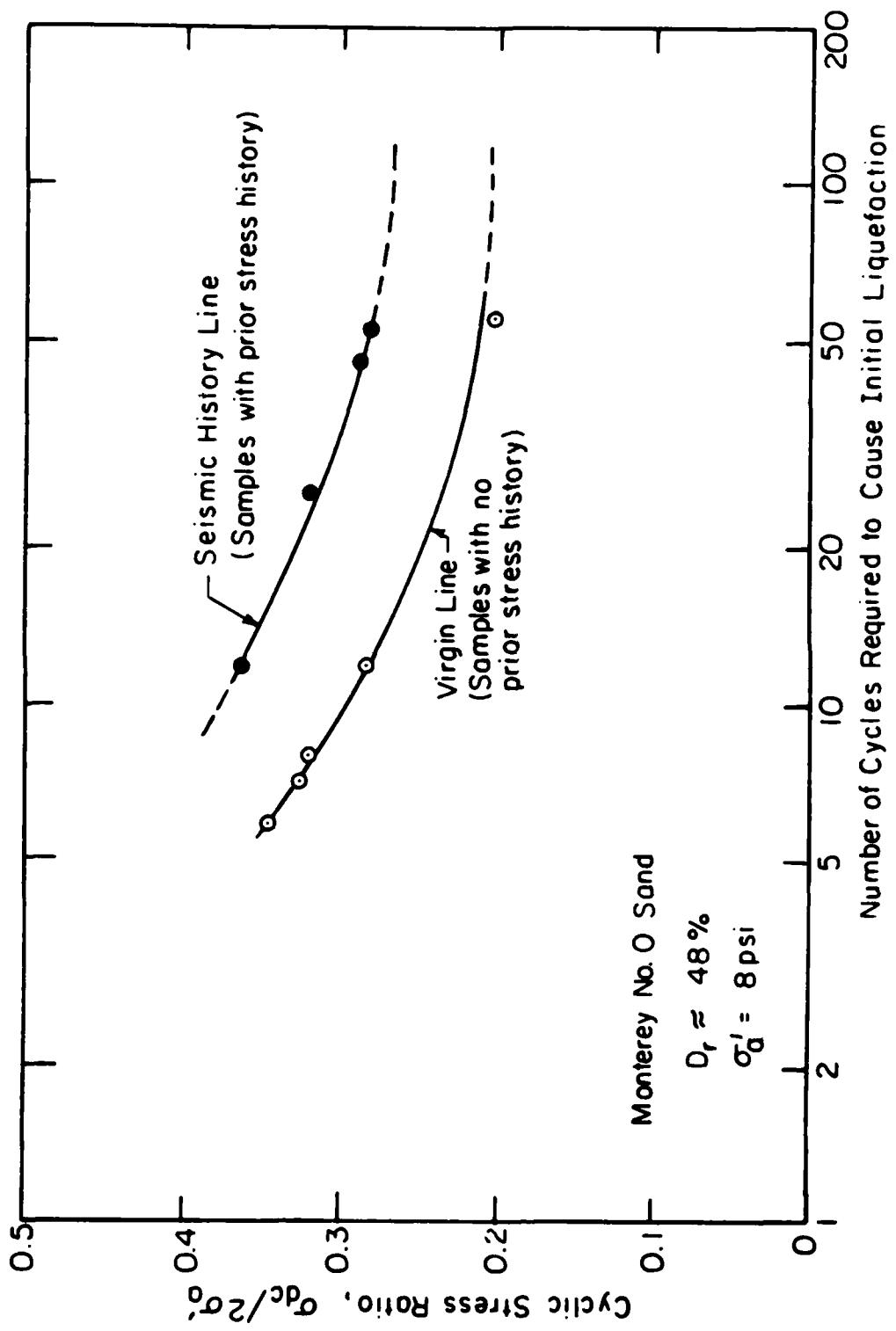
FIG. 5-4 SEISMIC HISTORY AND VIRGIN LINES FOR SAMPLES USED IN FREEZING STUDIES ($D_r \approx 48\%$)
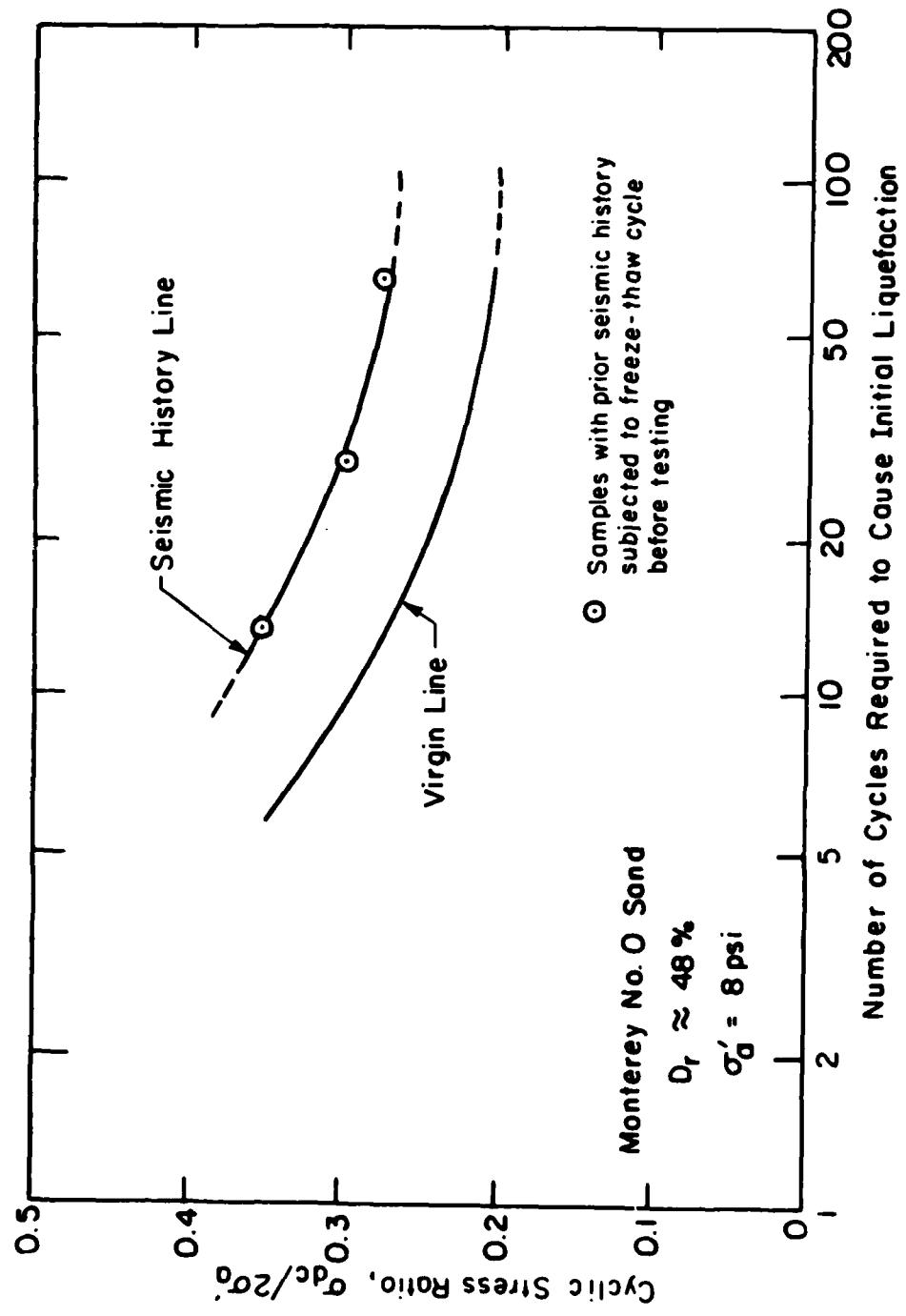
FIG. 5-5 EFFECT OF FREEZE-THAW CYCLE ON THE CYCLIC LOAD CHARACTERISTICS OF SANDS WITH PRIOR STRESS HISTORY

pressure was maintained at all times. The possible effects of removal of the confining pressure, after the sample is frozen, and of prolonged storage in a frozen condition thereby allowing the effect of ice creep, if any, to take place, were also important considerations and their possible influence on dynamic soil behavior was also required to be evaluated. Accordingly another set of identical specimens was prepared and given the same seismic history as for the baseline specimens and then frozen unidirectionally. The confining pressure was taken off and the entire cell was enclosed in a specially designed foam box where it could be effectively kept frozen for a long time, thus simulating prolonged storage often required during handling and shipping. Removal of the confining pressure without any disturbance to the sample simulated "perfect sampling." Crushed dry ice was packed in the annular space between the triaxial cell and the walls of the box. The specimen was kept frozen for more than 24 hours in this way, i.e., under the conditions of perfect sampling, thereby allowing the effects of ice creep, if any, to develop. The confining pressure was then restored and the triaxial cell was taken out of the freeze box and put in the foam container to allow it to thaw as described earlier. After more than 20 hours of thawing period, which ensured complete thaw, the triaxial cell was set in the cyclic loading device and subjected to cyclic loading until a pore pressure ratio of 100 percent and significant strains were developed. One again there was no difference in the liquefaction characteristics of the sample and that of the base-line specimens with similar seismic history (Fig. 5-6). Similar results for three additional specimens are also shown in this figure. Clearly the effect of previous strain history had been preserved and the
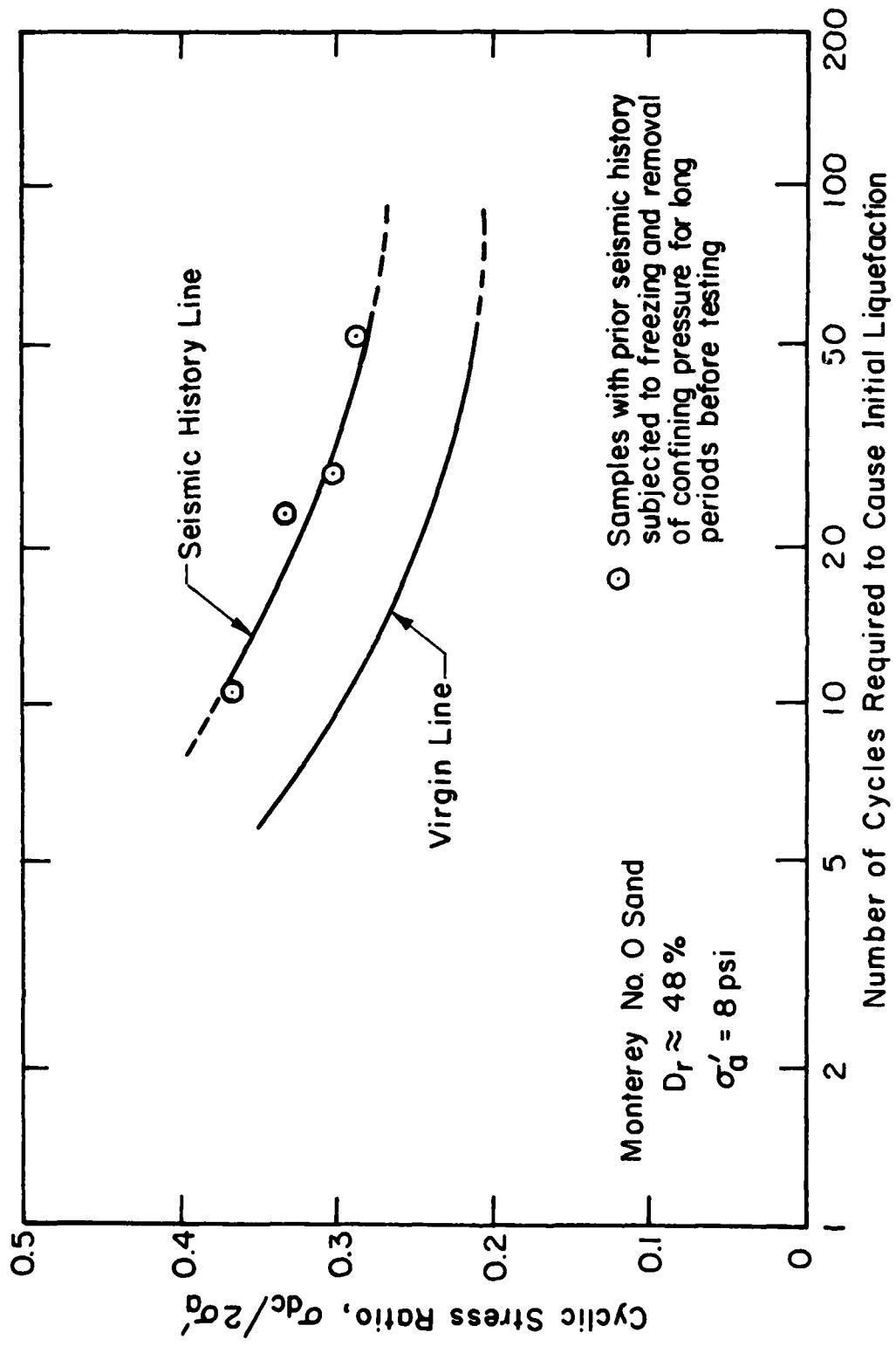
FIG. 5-6 EFFECT OF PERFECT SAMPLING (FOR PROLONGED PERIOD), FOLLOWING UNIDIRECTIONAL FREEZING, ON THE LIQUEFACTION CHARACTERISTICS OF SANDS WITH PRIOR STRESS HISTORY

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structure of the sand has remained practically undisturbed. In other words, the method of unidirectional freezing of sands as developed in this study seems to provide an effective means of preserving the structure of a sand. Such a method, when adapted for in-situ freezing and then coupled with a suitable coring procedure, would also appear to be suitable for securing undisturbed samples of much higher quality than can be achieved with current practice.

5.7 Adaptation of the Freezing Method to Freezing of 12 Inch Diameter Sample and Coring of 2.8 Inch Diameter Samples

The preceding studies throw considerable light on the effects of the proposed freezing method on the cyclic strength characteristics of carefully prepared laboratory samples not subjected to the effects of coring and problems associated with in-situ freezing. Consequently the large cyclic triaxial test facility, capable of testing 12 inch diameter specimens, was modified and used to explore the effects of coring frozen samples from blocks of frozen soil. The unidirectional freezing techniques were adapted for in-situ freezing of the 12 inch diameter specimens, and samples of 2.8 inch diameter were cored from these specimens. Following a brief description of the testing facility including the modification for unidirectional freezing and coring, handling and test procedures for the cored samples, a discussion of the test results will be presented in this section.

5.7.1 The 12 Inch Diameter Cyclic Triaxial Machine

The cyclic triaxial apparatus which uses a standard MTS closed loop system has been described by Wong (1971). For a detailed description of the apparatus including the MTS and the Sanborn recording system, the

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reader is referred to Wong's thesis. Major modifications were, however, made in relocation of the load cell and in the cap to permit freezing of the sample unidirectionally. In Chapter 3 a brief account of the relocation of the load cell and a system of 'O' rings to maintain the confining pressure while access is made to the sample, has already been presented.

5.7.2 The Freezing Cap

The 12 inch diameter specimens were frozen from top to bottom, similar in some respects, to the freezing down from the bottom of a bore hole. The cap was therefore designed to act as a cooling source. The lower half of the cap was made of aluminum and was capable of containing ethanol and crushed dry ice. The upper half of the cap, together with the neck which comes in contact with the metal chamber, was made of acrylic to provide necessary insulation.

5.7.3 Description of Sand and Method of Sample Preparation

Monterey #0 sand was used in this study and was obtained from the same stock pile as that used in the investigation involving push tube sampling described in Chapter 3. Various characteristics of this sand have already been presented in Chapter 3. Check tests on maximum and minimum densities were made on sand from different locations of the pile.

Details of the preparation of homogeneous specimens 12 inches in diameter and about 27 inches high using a specially designed pluviation method have also been presented in Chapter 3.

5.7.4 The Testing Program and Test Procedures

Utilizing the equipment, the method of sample preparation and the freezing technique described above, four different series of tests were

conducted to study the effect of freezing and coring on the cyclic loading characteristics of Monterey #0 sand with a prior seismic history. The first three series of tests were made on 12 inch diameter specimens, whereas the fourth series involved testing of 2.8 inch diameter cored samples.

The objective of each of the test series was as follows:

1. Test Series 4-A: To establish the cyclic load characteristics of a freshly deposited sand at a relative density of 60 percent.

2. Test Series 4-B: To establish the cyclic load characteristics of the sand samples which in addition to their being freshly deposited at 60 percent relative density had been given a known seismic history following the procedures used by Seed et al. (1975).

3. Test Series 4-C: To freeze 12 inch diameter specimens which had previously been given the same seismic history effects as were the specimens tested in Test Series 4-B.

4. Test Series 4-D: To test 2.8 inch diameter samples obtained by coring from the 12 inch diameter frozen specimens of the 4-C series.

Test Series A and B set up the basic relationships and the curves on a typical stress ratio versus number of cycles plot describing these relationships have been referred to as virgin and strain history lines respectively (Fig. 3-8). These relationships provide the framework or the basis to evaluate the effect of disturbance due to freezing and coring. Since the Test Series A and B are common to both "push tube sampling", the "block sampling" and "freezing and coring" studies, the reader is

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referred to Chapter 3 for a brief description of the test procedures and the results of each of these test series.

Test procedures for Series 4-C and 4-D are briefly described below.

Test Series 4-C

Utilizing the identical method of sample preparation as that used for series A and B, sand was poured to a relative density of 60 percent. After the surface of the specimen was levelled, the 'freezing cap' was placed on the top of the specimen. Subsequently steps from the application of the vacuum, removal of the mold, setting up of the triaxial chamber, application of confining pressure, saturation and finally the application of the seismic history effects were similar to the ones used for Test Series B. The specimen was now ready for freezing. The confining pressure (usually about 3.06 kg/cm^2) and the back pressure (of about 2.5 kg/cm^2) were kept unchanged. The entire triaxial chamber was surrounded by a specially designed foam mold to provide necessary insulation.

The freezing was started by pouring a mixture of ethanol and crushed dry ice through the neck of the cap into the aluminum container constituting the lower half of the cap. The bottom drainage line through which the back pressure acts was kept open for the water to flow out into the volume change measuring cylinder as the freezing progressed. A steady flow of water into the volume change cylinder indicated the advancing of the freeze front downwards starting from the cap. A cooler was used and dry ice was added intermittently to augment the cooling effect and to maintain an average temperature of about -60°F. The entire system worked very effectively and the water was seen flowing out of the completely

saturated specimen against a back pressure of 2.5 kg/cm^2. Freezing was
continued for four days and a complete record of the flow rate was main-
tained. The rate and amount of flow were consistent with the temperature
gradients and the phase change, as had previously been observed in
freezing 2.8 inch diameter samples. Lower temperature gradients on the
second day of freezing resulted in a somewhat longer duration of freezing.
At the end of the fourth day, the freezing was stopped. The cell and
back pressures were taken off and the triaxial chamber disassembled to
allow access to the frozen specimen. The specimen had been frozen to
about twenty-one inches in depth which was consistent with the theoretical
estimate based on the amount of the water flow resulting from phase
change. The freeze front had a smooth and square face resembling the
bottom of the cap.

Test Series 4-D

The frozen 12 inch diameter specimen was then carefully carried
to a Radial Drill Press set up for core drilling. A diamond core drill
was used to core several samples 2.8 inches in diameter and about 7 to
10 inches in length. Compressed CO_2 was used as the drilling fluid.

After the frozen core samples were cut to the right height, they
were set up in the triaxial machine for thawing under the same effective
confining pressure at which they were frozen. Free access to water was
provided through the bottom drainage line so that the water could be drawn
into the sample during thawing. After complete thawing, the samples were
saturated following the usual procedures of passing CO_2 and circulating
deaired water. Finally these samples were cyclically loaded to 100 percent
pore pressure ratios. The test results are shown in Fig. 5-7. The cored
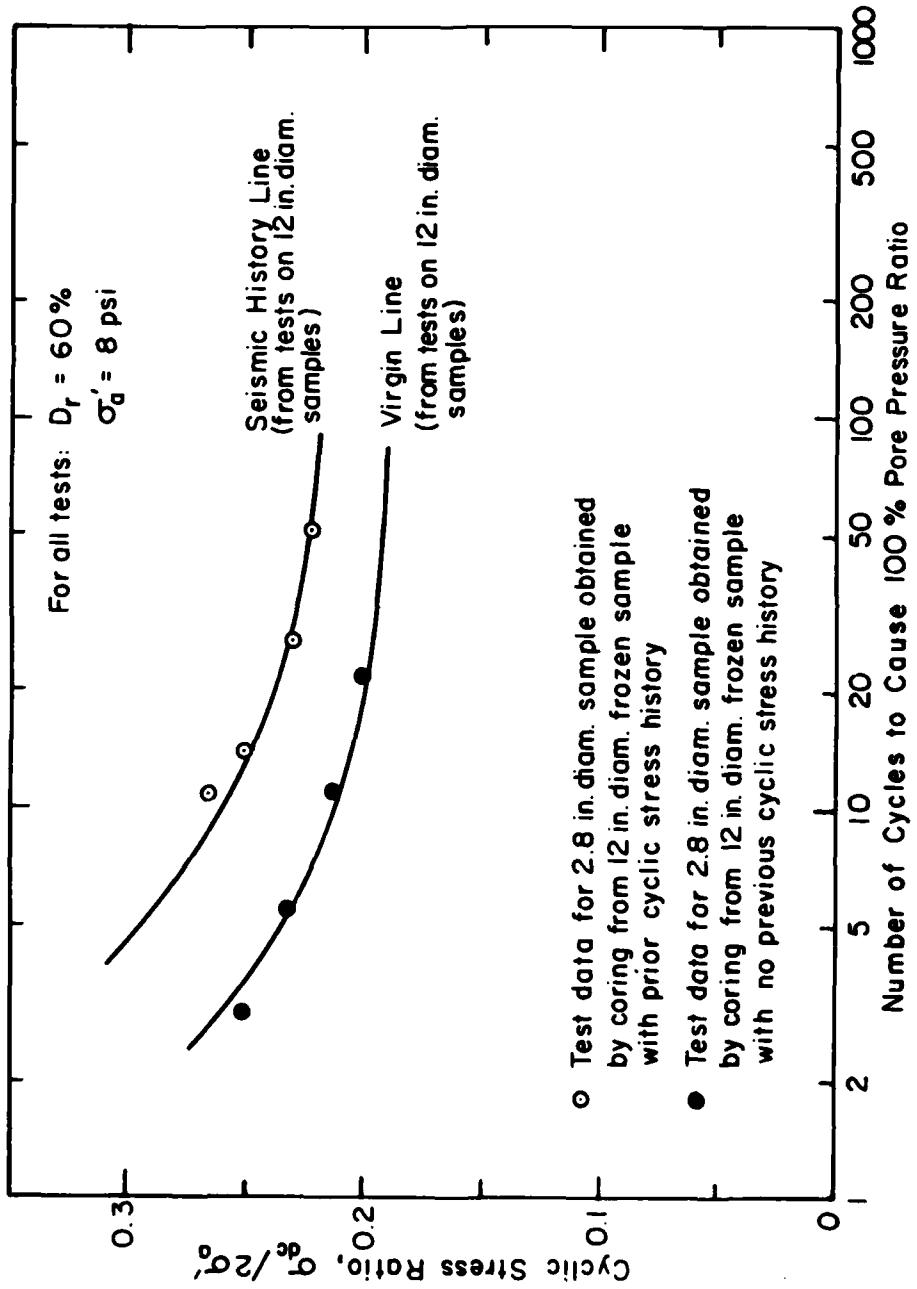
FIG. 5-7 EFFECT OF UNIDIRECTIONAL FREEZING AND UNDISTURBED SAMPLING (BY CORING) ON THE CYCLIC LOADING CHARACTERISTICS OF SAND

specimens showed no loss of increased resistance acquired by virtue of the seismic history effects given to the 12 inch diameter specimen from which the core samples had been obtained. Clearly the samples had remained practically undisturbed. To further confirm this result, tests were made on frozen samples cored from 12 inch diameter samples having no prior strain history. The results of these tests, also shown in Fig. 5-11, again indicate no change in cyclic load characteristics as a result of the freezing, sampling and thawing process.

5.8 Discussion

Small scale as well as full scale laboratory studies described in this chapter have shown that the proposed method of soil sampling by in-situ freezing and coring, where drainage is not impeded in the direction of the movement of the freeze-front and the confining pressure is maintained during freezing, provides an effective means to obtain undisturbed samples of saturated sands of higher quality than can be achieved with other currently used procedures. The method seems to cause practically no disturbance to the dynamic strength characteristics of the sand used in this investigation. It should be noted, however, that the various variables such as the coolant temperature, the percent of fines in the sand, the confining pressure and the depth of sampling can influence both the efficiency and effectiveness of the proposed method. Recent work by Yoshimi et al. (1978) throws significant light on the influence of these variables on the expansive strains during one dimensional freezing, according to which an increase in the percentage of fines would require higher confining pressures to control volume expansion. For example, for saturated sands containing less than 5 percent fines, the expansive strains

during one dimensional freezing decreased with an increase in the sur-
charge pressure until they became less than 0.1 percent when the sur-
charge exceeded about 0.3 kg/cm^2 which corresponds to the overburden
pressure at a depth of about 8 ft. For 6 percent fines the expansion
strain was about 0.13 percent. For clean sands and sands with percen-
tage of fines equal to 5 percent or less at depths of about 15 ft. or
greater, normally considered critical for liquefaction, the proposed
method should work satisfactorily. The rate or speed of freezing is
affected by the coolant temperature. A slower rate of cooling should
result in none or extremely small expansive tendencies. A better under-
standing of these and other considerations, as also pointed out by
Yoshimi et al., should lead to an effective utilization of this method
for obtaining undisturbed samples of sands below the ground water table.

Notwithstanding the expensive and time consuming aspects of the
proposed freezing method, there are definite advantages in shipping,
handling and setting up for testing of frozen samples. Since the dis-
turbance effects associated with the shipping, extruding and setting up
of a thawed sample are eliminated, one of the most difficult, delicate,
and time-consuming aspects of handling undisturbed samples becomes very
easy and efficient.

CHAPTER 6

INFLUENCE OF THE DISTURBANCES CAUSED BY
SAMPLE TRANSPORTATION AND SAMPLE HANDLING
IN THE LABORATORY ON CYCLIC STRENGTH CHARACTERISTICS OF SANDS

6.1 Introduction

It has been recognized that the usefulness of an undisturbed sample may be seriously impaired by disturbance to the sample during: (i) transportation or shipment of the sample to the laboratory; (ii) storage of the sample; and (iii) preparation of the sample for laboratory testing.

Disturbance due to shipment can be particularly serious in the case of loose sandy or silty cohesionless soils because transportation in vehicles over long distances is likely to cause vibrations resulting in significant changes in void ratio.

Inadequate storage and improper sealing of the ends of the sampling tube can cause a loss of water; and chemical and physical changes may also take place in the soil.

Extruding and setting up of a cohesionless sample for testing is an extremely delicate and difficult operation. The force required to extrude a sample and a possible slumping of a saturated sandy sample after extrusion can be significant sources of disturbance.

In this chapter several studies related to the influence of disturbance caused by currently-used methods of transporting and handling samples in the laboratory on the measured cyclic loading characteristics of sands are presented.

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6.2 Review and Objectives of the Present Studies

In cases where tests require special care in the preservation of the structure of a sand, freezing techniques are utilized to transport the samples without disturbance. The U. S. Army Corps of Engineers has recently been using the freezing technique (1972) to stabilize the structure of undisturbed samples. Samples are usually freely drained first and then frozen by spraying liquid nitrogen on the sampling tube or surrounding the tube with crushed dry ice. After the samples are completely frozen, they are transported to the laboratory in an insulated container or in a freezer such that frozen conditions are maintained until testing.

Ishihara and Silver (1978), Horn (1978), Houps (1978), Marcuson et al. (1978), Espana et al. (1978) and Walberg (1978) have reported freezing drained samples for shipment and/or handling and have detected no apparent volume changes. The effects of freezing drained samples and subsequent thawing on the dynamic strength characteristics have also been reported in terms of comparative cyclic load tests on undisturbed samples drained but not frozen prior to shipment to the laboratory and undisturbed samples drained and frozen prior to shipment (Walberg, 1978). The results indicated no significant difference in the liquefaction behavior of the sand tested. Somewhat different results were reported by Ishihara (1977), however, who found that sands which had 10 percent fines had their strength reduced by about 25 percent through the use of a similar freezing technique. Apparently the presence of fines did not allow for satisfactory drainage.

While the preceding results provide important insights into the effects of freezing of drained samples on cyclic strength characteristics,

the variability of soil from specimen to specimen including the variability of disturbance effects due to sampling and possible additional disturbance due to the shipment of drained but not frozen samples which provided the basis for comparison are likely to influence the test results. Clearly a more rigorous basis is required in order to determine the influence of shipping on sample disturbance. Similarly, the influence of the disturbance due to poor or improper laboratory test specimen preparation of undisturbed samples on the cyclic strength behavior has not been adequately evaluated.

Since the basic relationships - the virgin and seismic history lines - which provide the necessary framework for comparison had already been established as described in Chapters 3 and 5, it was readily possible to investigate the effect of the disturbances due to freezing for shipping and due to laboratory handling on the seismic strength characteristics of Monterey #0 sand. Accordingly, studies were undertaken to evaluate: (i) the influence of freezing samples after free drainage before shipping on the cyclic strength characteristics of undisturbed samples; (ii) the quality of undisturbed samples obtained when there is poor or no drainage prior to freezing; and (iii) the effects of disturbances due to poor handling during extruding and laboratory test specimen preparation on the cyclic strength characteristics of undisturbed samples.

A brief description of the testing program, the testing procedure and the results of the tests are presented in this chapter.

6.3 Disturbance Effects Due to Freezing for Transportation

Since the current practice for freezing samples in the field before

shipping is by spraying liquid nitrogen on the sampling tube or sur-
rounding the tube with crushed dry ice, this method of freezing will be,
hereafter, called the "all around" freezing method as opposed to the
"unidirectional" freezing method described in Chapter 5.

6.3.1 Testing Program

It may be noted that in order to study the influence of only one
source of disturbance, the other sources of disturbance were avoided
or eliminated by carrying out "all around" freezing on samples which had
not been subjected to any sampling operation, not even "perfect sampling".
The testing program therefore consisted of preparing samples to known
dynamic characteristics and then subjecting them to "all around" freezing.
The size of the samples was 2.8 inches and the standard triaxial equip-
ment needed only slight modifications in the chamber and drainage lines,
which were made of metal, to adapt the whole system to "all around"
freezing.

The testing program was planned along the same approach as was
utilized in studying the effect of disturbance due to tube or block
sampling; that is, a known framework was first established to act as the
basis for comparison.

Test Series 6-A and 6-B

Test Series 6-A and 6-B were carried out to establish a basis for
comparison by testing tamped specimens prepared using the following pro-
cedures described by Mulilis et al. (1975). Monterey #0 sand was used
for sample preparation. The description of the sand is the same as that
described in Chapter 3 except that it had been obtained from a different
stock-pile and its maximum and minimum densities were respectively 89.5 pcf

and 105.3 pcf. Specimens of 2.8 inch diameter and about 6.5 inches in height were prepared identically to a relative density of about 48 percent; they were then saturated and consolidated under a cell pressure of 2.06 kg/cm^2 and a back pressure of 1.5 kg/cm^2. One set of these specimens was then subjected to cyclic triaxial tests until a pore pressure ratio of 100 percent was reached. A virgin line (i.e., with no prior strain history effects) was then established. Another set (Test Series 6-B) of these specimens was first subjected to a known seismic history using procedures described by Seed, Mori and Chan (1976) and then cyclically loaded to the 100 percent pore pressure ratio conditions. Thus a cyclic loading characteristic curve influenced by seismic history was established, and was referred to as the seismic history line (see Fig. 5-6 of Chapter 5).

Test Series 6-C

In order to investigate the effect of the "all around" freezing method on a freely drained sample with known seismic characteristics, a test was set up with a specimen of similar characteristics and seismic history to those of Test Series 6-B. The specimen was then allowed to drain freely while maintaining the confining pressure constant. Top and bottom drainage lines were opened to the atmosphere and water was allowed to drip freely through the bottom drainage line for several hours until free draining was almost complete.

"All around" freezing was then accomplished by first introducing cooled ethanol into the triaxial chamber. An aluminum chamber was used and all drainage lines had been changed from nylon to brass tubing to avoid cracking or breaking of nylon tubing upon cooling to very low

temperatures. The aluminum chamber was then surrounded by crushed dry ice to lower the temperature of the ethanol. The entire triaxial set-up was enclosed in a foam insulating container and the temperature of the ethanol was kept around -75°F. After complete freezing of the specimen was achieved, the confining pressure was reduced to zero and the alcohol was carefully removed from the chamber. No changes in the diameter and height of the specimen were noticed. The triaxial cell was reassembled while the specimen was still frozen, and the cell air pressure restored to its original value. The sample was then allowed to thaw while surrounded by the room temperature. Finally the specimen was saturated and tested to determine its cyclic loading characteristics. The result of this test is shown in Fig. 6-1 which indicates no loss of prior strain history effects.

It appears therefore that the currently used methods of free drain-ing and then freezing samples will preserve the integrity of the structure during shipping and handling. It should be noted, however, that this was a perfect sample and it had not been subjected to the disturbance effects of a normal sampling operation.

Test Series 6-D

Finally to explore the effects of insufficient or no drainage on the quality of a sample stabilized by the "all around" freezing method, another identical specimen was set up and subjected to the same seismic history effects as those of Test Series 6-B. No drainage was allowed and the top and bottom drainage lines were kept closed during the freezing process. Alcohol was introduced into the chamber while maintaining the confining pressure, and the specimen was frozen following the procedures
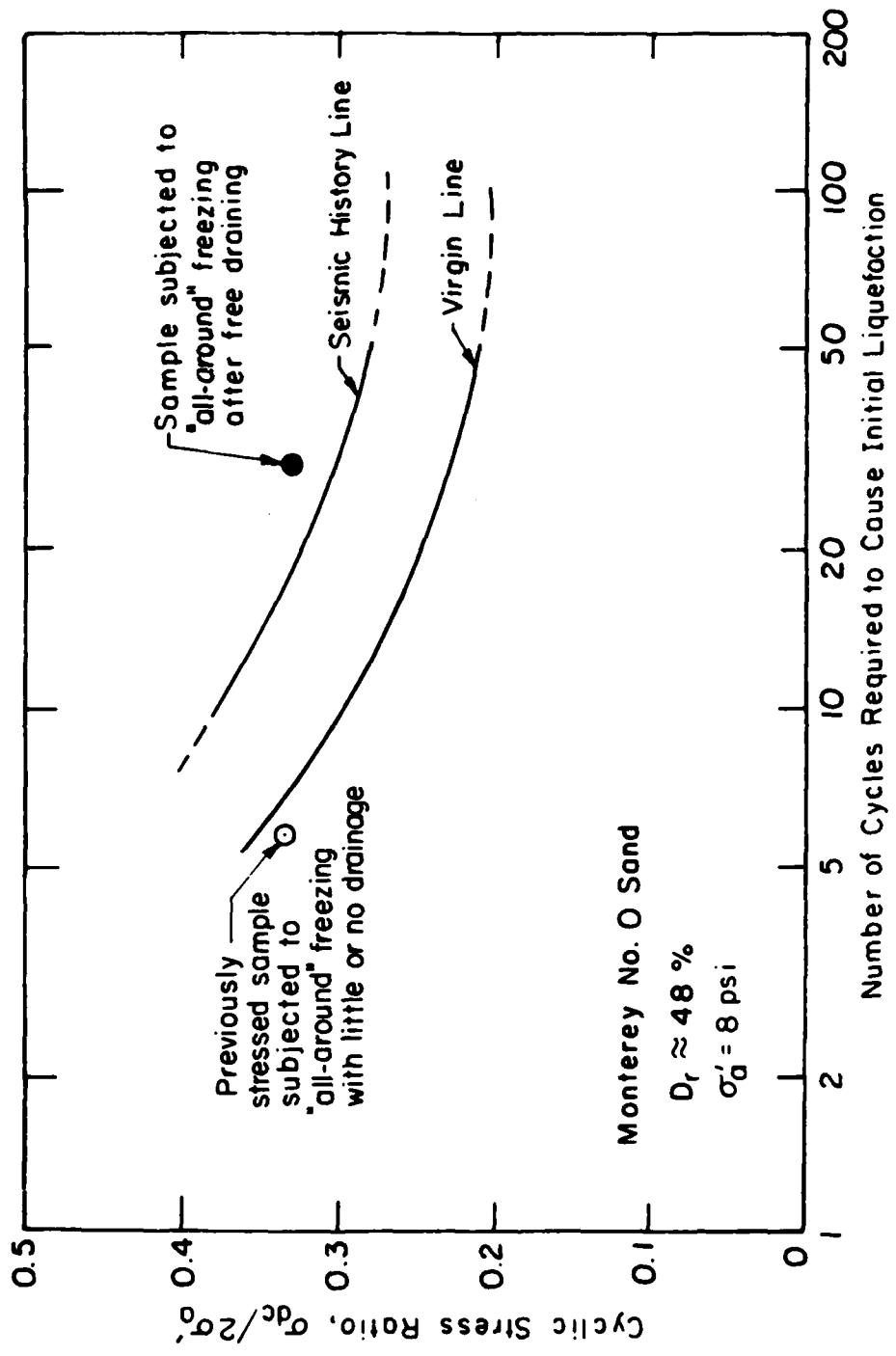
FIG. 6-1 EFFECT OF "ALL-AROUND" FREEZING ON CYCLIC LOAD CHARACTERISTICS OF TUBE SAMPLES FROM BLOCK WITH PRIOR STRESS HISTORY

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described earlier for "all around" freezing. After complete freezing of the specimen was achieved, the confining pressure was reduced to zero, the alcohol removed and the chamber disassembled as usual to permit access to the sample. Diameter and height readings were taken. Whereas negligible change was noticed in the diameter, the height increased by 0.24 inches due to expansion from freezing. The cell was reassembled while the specimen was still frozen and the chamber pressure restored as before. The top drainage line was then kept open while the sample was thawing under room temperature. After thawing was completely ensured, the specimen was cyclically loaded to determine its dynamic strength characteristics. Figure 6-1 shows that all the beneficial effects of the previous seismic history were lost and that the test result fell back to the virgin curve indicating that the method of "all around" freezing of saturated samples of sands, without the possibility of drainage before freezing, severely disturbs the structure of the saturated samples.

6.4 Disturbance Effects Due to Poor Handling for Laboratory Sample Preparation of Undisturbed Samples

6.4.1 The Testing Program

In order to provide a basis for determining the characteristics of a poorly handled sample, the characteristics of a carefully handled undisturbed sample must first be established. Accordingly, the testing program used to establish the test results on undisturbed samples reported in Chapter 3 was used as a basis for comparison. In summary, a complete testing program includes three test series on 12 inch diameter samples and the fourth and fifth test series on 2.8 inch diameter samples taken from the 12 inch diameter samples.

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The first two test series which have already been described in
Chapter 3 set up the basic relationship between the number of cycles
to produce 100 percent pore pressure ratio and the cyclic stress ratio
for virgin and previously strained samples. Figure 3-8 of Chapter 3
shows these relationships.

The third test series involved sampling from the 12 inch diameter
specimens which had previously been given known seismic history char-
acteristics. Hvorslev's fixed piston sampler was used and the details
have been presented in Chapter 3.

The fourth test series involved carefully extruding, setting up
and testing of the undisturbed samples taken in Series 3. Figure 3-10
of Chapter 3 presents the results of this test series.

The fifth series of tests involved preparation of 12 inch diameter
specimens to the same seismic history characteristics as for the fourth
test series and then extracting undisturbed samples as before by Hvorslev's
fixed piston sampler. The only difference between this and the previous
(fourth) test series was that the undisturbed samples were subjected to
some type of disturbance during the handling process. In one case the
disturbance was caused by use of a poor extruding technique which involved
free standing of the sample during the extruding process causing some
slumping and deformation of the sample resulting in loosening. Whereas
the carefully undisturbed samples had indicated an increase in relative
density by about 6 percent due to the sampling process, this sample did
not exhibit any increase in density measured after the sample was extruded
and set up for testing. The results also fell back to the virgin line
indicating that the disturbance had caused the sample to loosen which in
turn wiped out the prior history effects (Fig. 6.2).
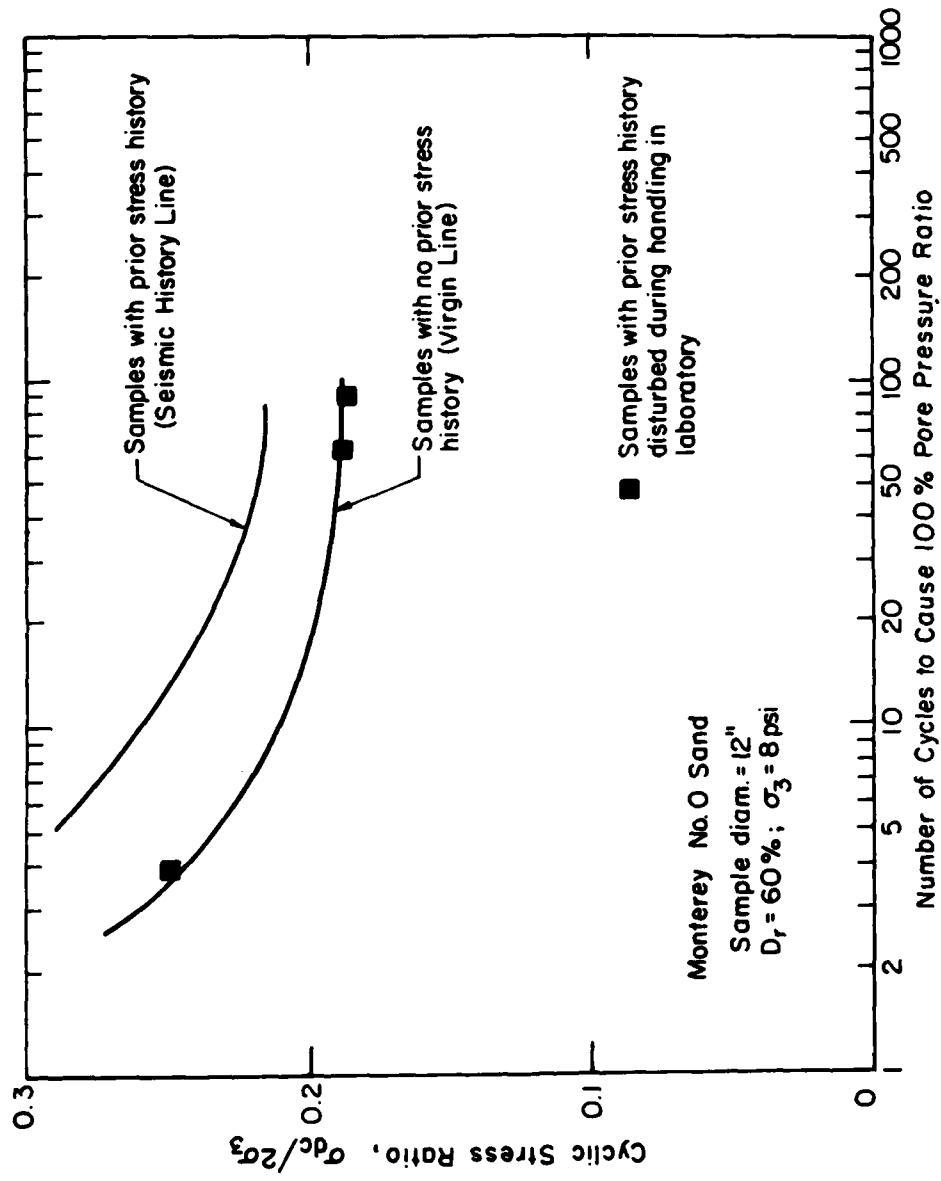
FIG. 6-2 EFFECT OF DISTURBANCE DURING HANDLING OF 'UNDISTURBED' SAMPLES TAKEN FROM BLOCK WITH PRIOR STRESS HISTORY

Another sample was disturbed during the placing of the membrane.
This caused some variation in the sample diameter and the verticality.
The test results corrected to a relative density of 60% again indicated
a loss of the strain history effects.

A third sample was disturbed by rough handling during extraction
of the sampling tube and setting up the sample for testing. Once again,
the test results corrected to a relative density of 60% showed a complete
loss of all prior strain history effects (see Fig. 6-2).

6.5 Discussions

On the basis of the limited number of tests reported in this
chapter on the effects of freezing prior to shipping, field freezing
of samples after they have been drained appears to offer great promise
as a means of stabilizing the structure of sand samples, thus preventing
disturbance due to shipping or handling in the laboratory. The effective-
ness of this method ("all around" freezing), however, depends on the
degree of drainage prior to freezing. If the sample contains a large
percentage of fines, sufficient drainage might not be achieved and the
structure of the soil can be severely disturbed by freezing; in this
case the "unidirectional" freezing technique explained in Chapter 5 may
be used to freeze the sample. Studies of the influence of the amount of
fines on the drainage time and on the effectiveness of the freezing
technique would be worthwhile.

It appears that the influence of disturbance effects due to extrud-
ing and handling of laboratory samples can be the cause of a significant
loss of the resistance to cyclic loading as a result of a previous seismic
history. However, if the disturbance effects cause densification of a

contractive sample, this would tend to offset any other type of loss in resistance and the results would require careful interpretation.

CHAPTER 7

CONCLUSIONS

The studies described in the preceding pages were carried out to investigate by laboratory experimentation the effects of undisturbed sampling utilizing block, push-tube and freezing techniques and the influence of disturbance due to shipping and handling on the cyclic strength characteristics of Monterey #0 sand. All testing was carried out under stress-controlled cyclic triaxial test conditions.

The principal conclusions which may be drawn directly from this study are:

1. Block sampling by advance trimming and sampling using a technique similar to that developed by Geotechnical Engineers, Inc. caused minimal density change in the Monterey #0 sand deposit placed at a relative density of 60 percent.

2. The combined effect of the disturbances due to block sampling by advance trimming and laboratory preparation was to result in only a partial loss of the resistance gained due to previous seismic history effects. Block sampling may therefore provide a very high quality sample not obtainable by any other conventional method currently available.

3. Push-tube (Hvorslev-fixed piston) sampling caused density changes (densification) of Monterey #0 sand with a relative density of about 60 percent. A relatively larger relative density increase (about 10 percent) was noticed in the case of freshly deposited samples as compared with about 6 percent increase in the case of

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samples previously subjected to seismic history effects, indicating that the less resistant structure of virgin soil deposits is likely to undergo somewhat more pronounced density changes during sampling than a more resistant structure of a deposit with a history of past loading.

4. The densification of the sand by push-tube sampling should apparently involve relative movements between sand grains and therefore some loss of the effects of prior strain history. The test results indicated that this loss may be compensated by an increase in density and possibly also by some straining effects due to sampling such that only a small loss of strain history effects is indicated as the result of the sampling procedure.

5. The test data on virgin samples indicated that the measured strength of undisturbed samples can be explained simply as a result of densification during sampling. The effects of straining during sampling therefore appear to be negligible.

6. Laboratory studies on freezing of saturated samples of Monterey #0 sand have indicated that if the confining pressure is maintained and drainage is not impeded, i.e., there is a free drainage on the unfrozen s⁵ of the freezing interface, then the volume changes c .ng freezing are insignificant and the cyclic strength characteristics are not altered by the freezing and subsequent thawing process.

7. In-situ freezing by the above method, simulated by freezing 12 inch diameter samples, followed by sampling of 2.8 inch diameter samples with a core drill provided samples whose prior strain history characteristics remained essentially unchanged.

8. The currently-used method of free draining samples of cohesionless soils and then freezing them by surrounding the sampling tube with dry ice will preserve the integrity of the structure during shipping and handling. The effectiveness of this freezing technique, however, seems to depend on the degree of drainage prior to freezing. If the sample contains a large percentage of fines, insufficient drainage may make the "all around" freezing technique ineffective in preserving the structure of the undisturbed sample in which case the "unidirectional freezing technique" offers great promise as a means of stabilizing the structure of the sand against disturbances during transportation and handling.

9. "All around" freezing (by surrounding the tube with dry ice or by spraying liquid nitrogen on the tube) of saturated samples of sand without prior drainage severely disturbs the structure of the saturated samples.

10. Disturbance effects due to poor handling during laboratory sample preparation of undisturbed samples of sands obtained from a deposit of 60 percent relative density could result in (1) a complete loss of prior strain history effects as well as the loss of density gained during sampling; (2) a partial loss of strain history effects with minimal change in sampled density; or (3) an additional densification of virgin samples with a corresponding increase in cyclic strength characteristics. Therefore the influence of disturbance due to sample handling requires careful interpretation in evaluating the significance of cyclic load test data.

It should be rememberd in evaluating the results of the study that the majority of the tests were performed on sand which had been deposited by pluviation and then been subjected to a prior cyclic history to give it some sensitivity to disturbance. For such a sand with a relative density of 60%, the results indicate the following approximate effects of sampling on different factors influencing the cyclic loading resistance of the sand:

Factor	Block Sampling	Tube Sampling	Controlled Freezing
Density	Slight loosening (strength reduced about 5%)	Some densification (Strength increased about 10 to 16%)	No change
Long-term Loading	No effect	No effect	No change
Structure or Fabric	Little change	Little change	No change
Seismic History	Slight loss of strength (about 5%)	Slight loss of strength (0 to 5%)	No change
Net effect	Slight loss of strength (about 10%)	Slight gain in strength (about 5 to 15%)	No change

For natural deposits however at the same relative density a similar sand is likely to have acquired considerable additional resistance to cyclic loading as a result of the effects of long-term loading or sustained pressures. This effect may easily increase the resistance to cyclic loading by as much as 75 to 100%. Such natural sands will therefore be much more vulnerable to a loss of strenqth due to sample disturbance than the relatively insensitive sand used in the laboratory

investigation. For such natural deposits at a relative density of 60%, the effects of different methods of sampling are more likely to be approximately as follows:

Factor	Block Sampling	Tube Sampling	Controlled Freezing
Density	Slight loosening (Strength reduced about 5%)	Some densification (Strength increased $\simeq$ 15%)	No change
Long-term Loading	Some loss of strength (estimated $\simeq$ 5%)	Some loss of strength (estimated $\simeq$ 25%)	Probably no change
Structure or Fabric	Little change	Little change	No change
Seismic History	Slight loss of strength (about 5%)	Slight loss of strength (about 5%)	No change
Net effect	Some loss of strength (about 15%)	Some loss of strength (about 15%)	Probably no change

For natural sands with a relative density of about 85%, tube sampling will inevitably cause considerable dilation and associated strength loss together with a greater loss of the resistance acquired as a result of the sustained pressures applied over long periods since deposition; thus the net loss of resistance may be of the order of say 50 to 65%. This would not be the case with block sampling or controlled freezing techniques.

While the above are admittedly estimates based on current knowledge of sand characteristics, it is believed they represent reasonable approximations of the potential effects of sampling in natural deposits.

It may be noted that for natural deposits with a relative density of about 60%, the cyclic loading resistance of block samples may be expected to be similar to that of tube samples, but for very dense natural deposits, block samples are likely to show much greater resistance to cyclic loading than tube samples. However in both cases the measured resistance is likely to be less than that of the natural deposit, the difference increasing as the density increases. Some evidence of this is seen in the test data reported by Marcuson and Franklin shown in Fig. 4-1 and by the data presented in Fig. 2-3.

It is believed that in dealing with test data on sands, some estimates of the influence of disturbance on the various factors affecting the cyclic loading resistance similar to those shown above, should always be made. By this means, improved assessments of field performance can be made and apparent anomalies can be understood.

It is useful in studying the effects of sampling disturbance to make simple sketches depicting the estimated effects of different factors, similar to that shown for a hydraulic fill in a non-seismic region in Fig. 7-1 or that shown for a very dense natural deposit in Fig. 7-2, to arrive at an estimate of the significance of disturbance on the final test results.

Where such effects cannot be reliably assessed however, it appears that the only recourse may be to use an appropriate freezing procedure to obtain higher quality undisturbed samples and hence a more representative value of the in-situ properties of a soil deposit in tests conducted at low strain levels.
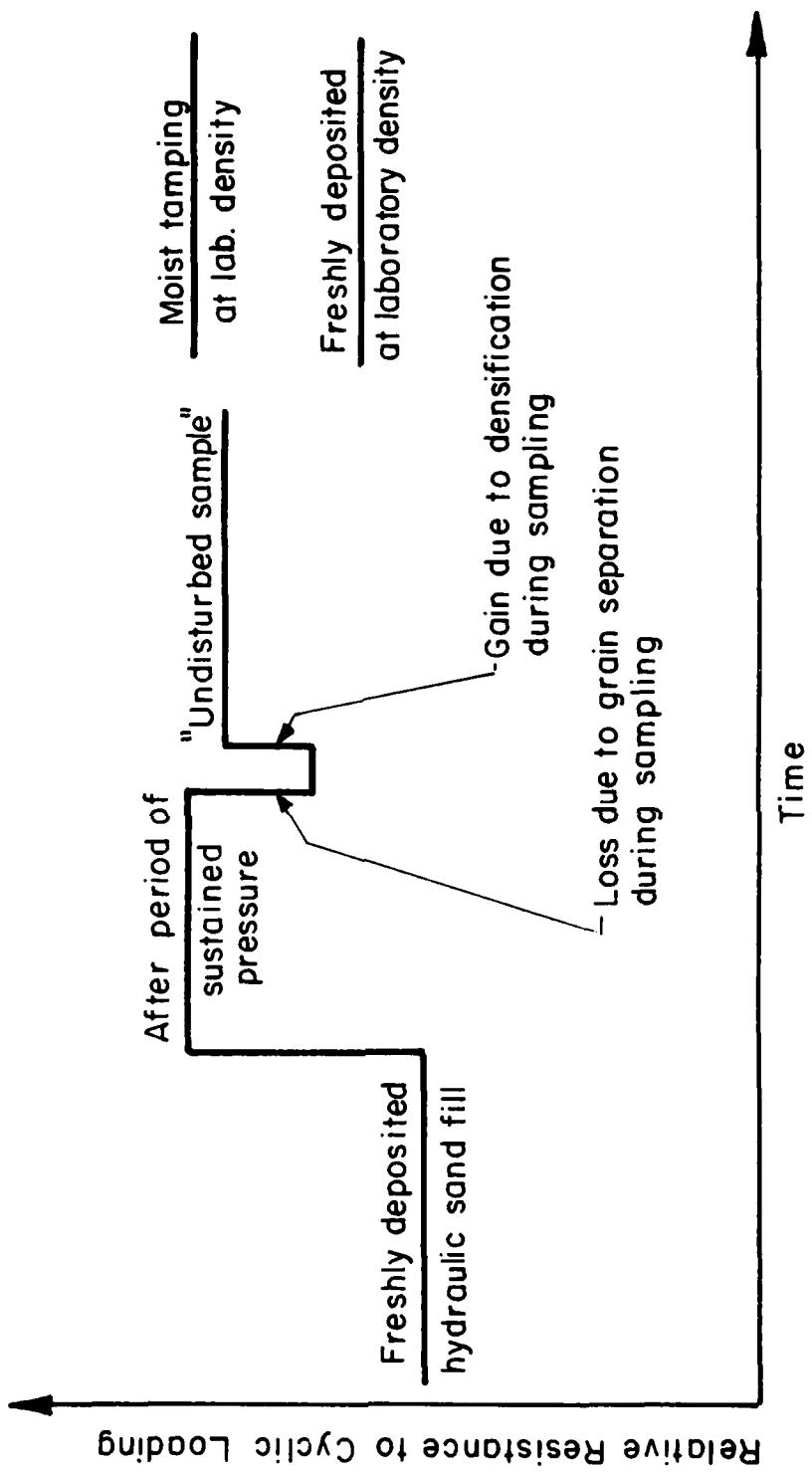
FIG. 7-1 EFFECT OF UNDISTURBED TUBE SAMPLING AND SAMPLE RECONSTITUTION ON RESISTANCE TO CYCLIC LOADING FOR HYDRAULIC SAND FILL FROM NON-SEISMIC REGION

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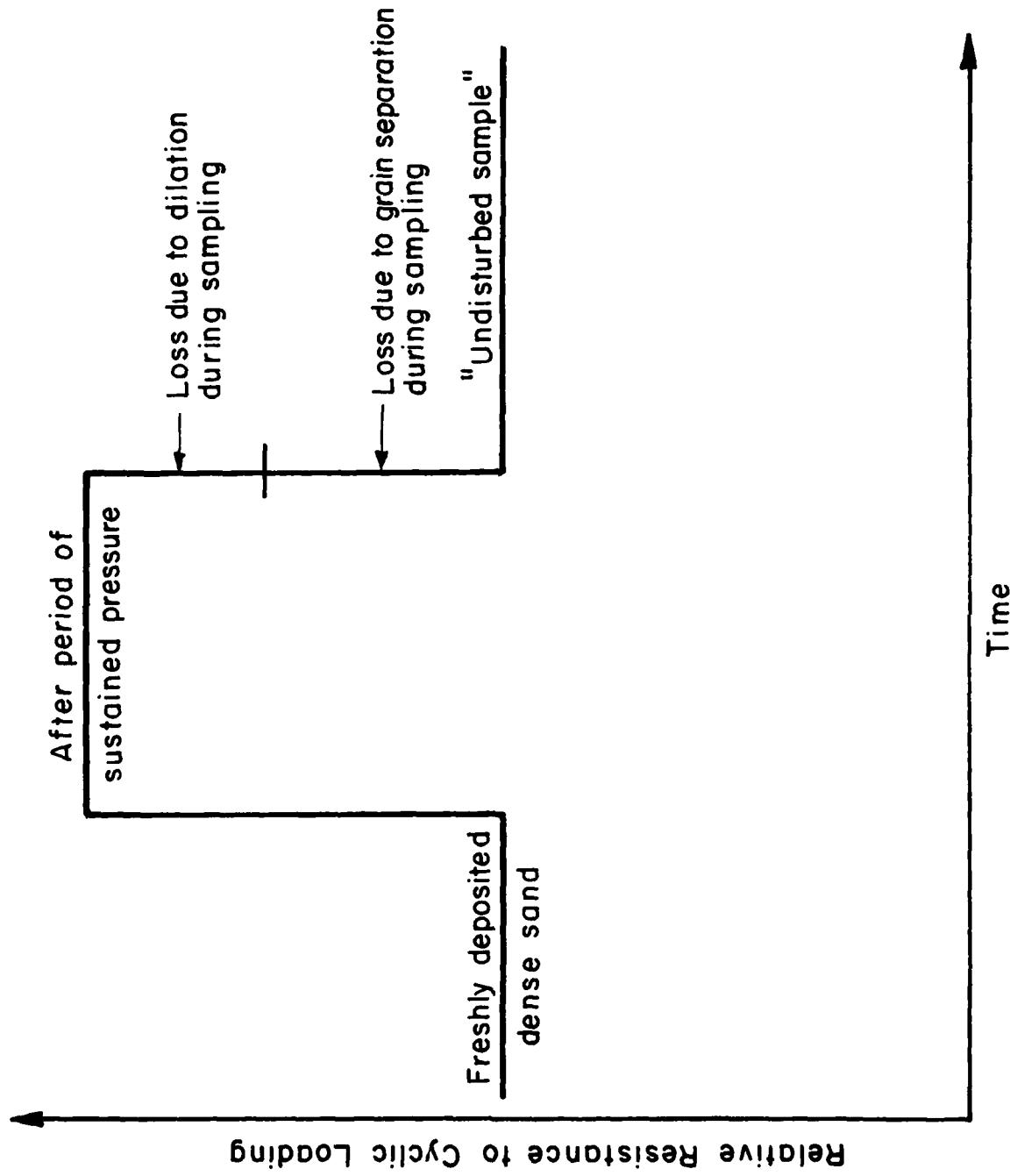
FIG. 7-2   EFFECT OF UNDISTURBED TUBE SAMPLING ON RESISTANCE TO CYCLIC LOADING OF DENSE
NATURAL DEPOSIT OF SAND

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